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Technology Review

MIT's Magazine of Innovation

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A prototype of a clear holographic disc holding 300 gigabytes of data

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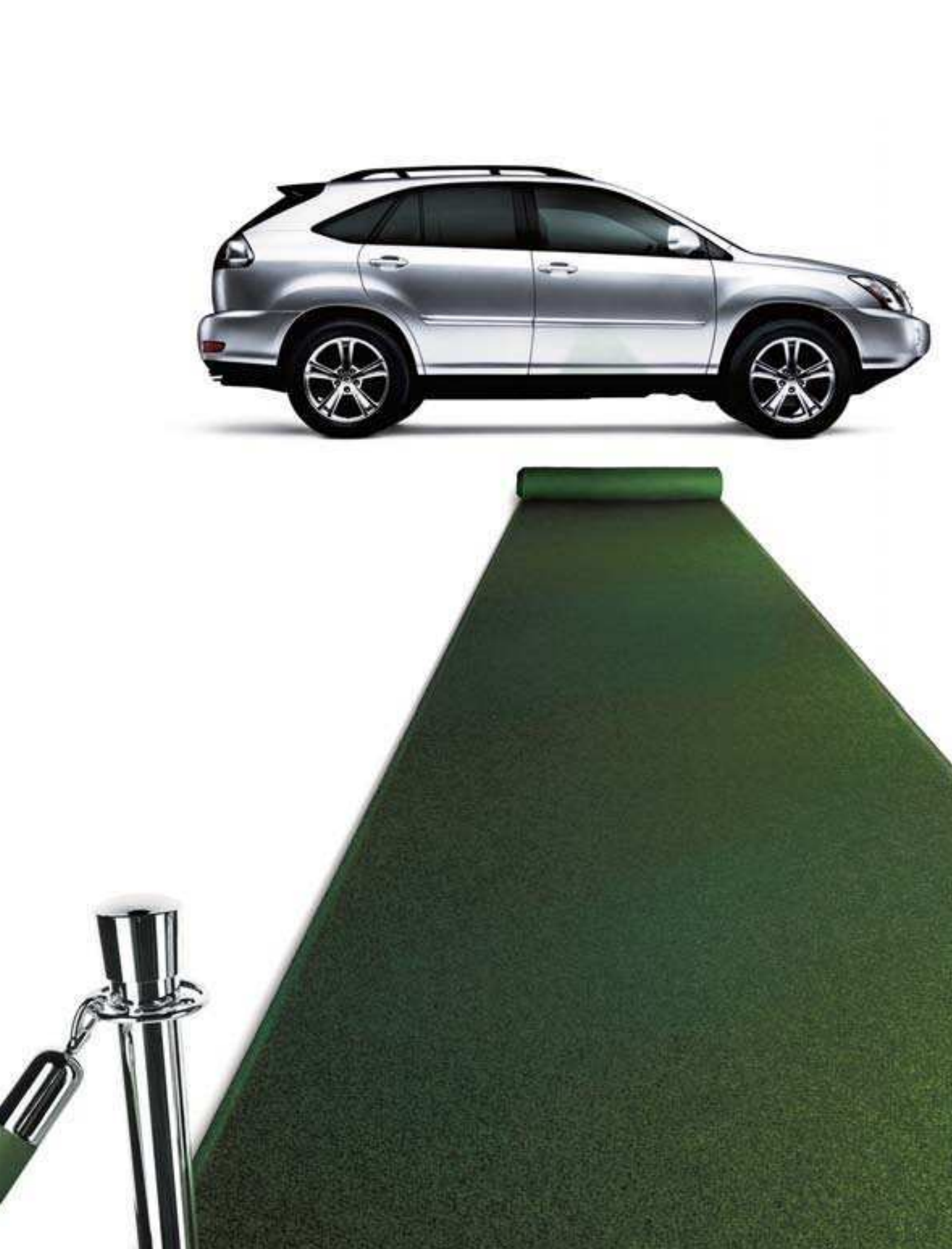

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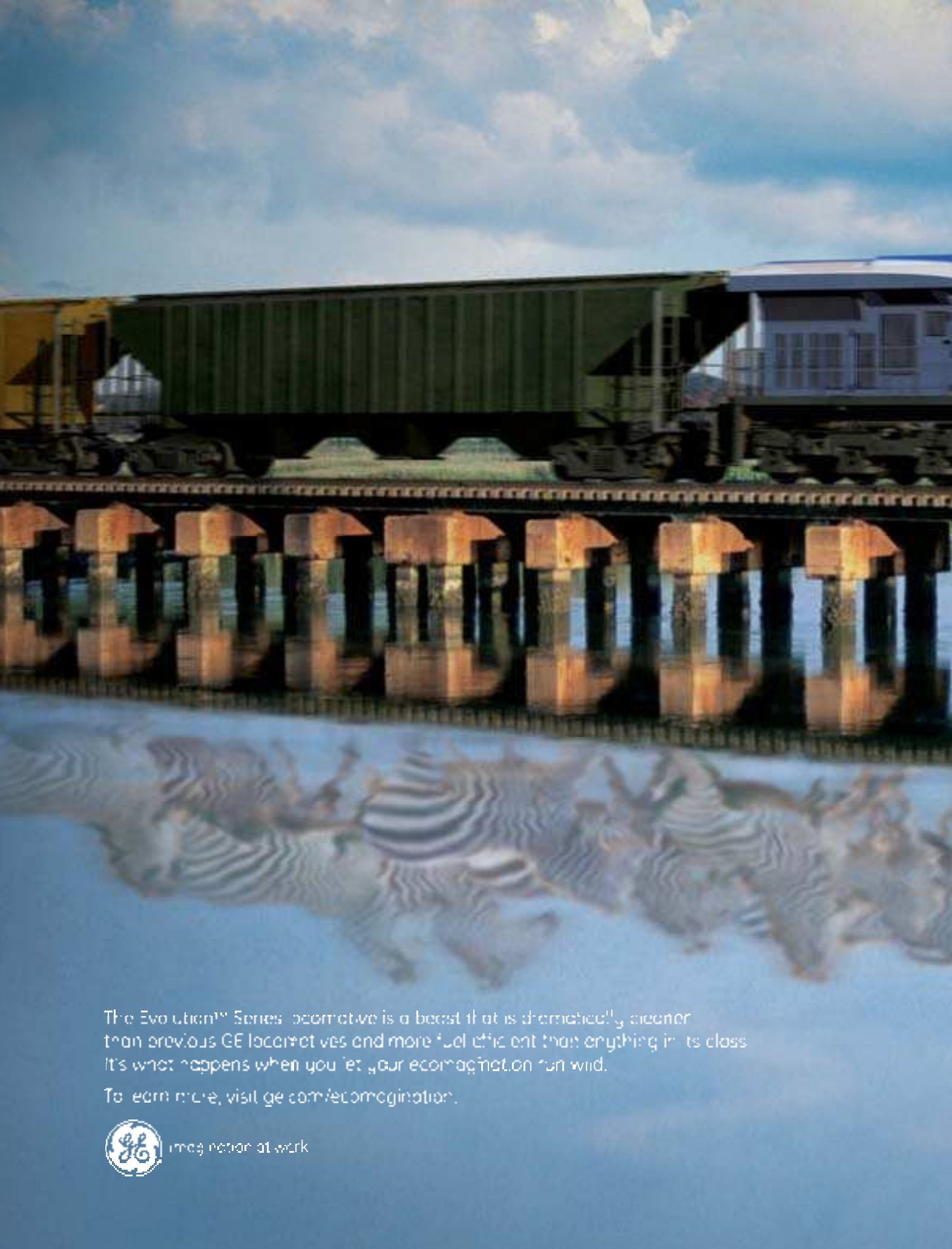

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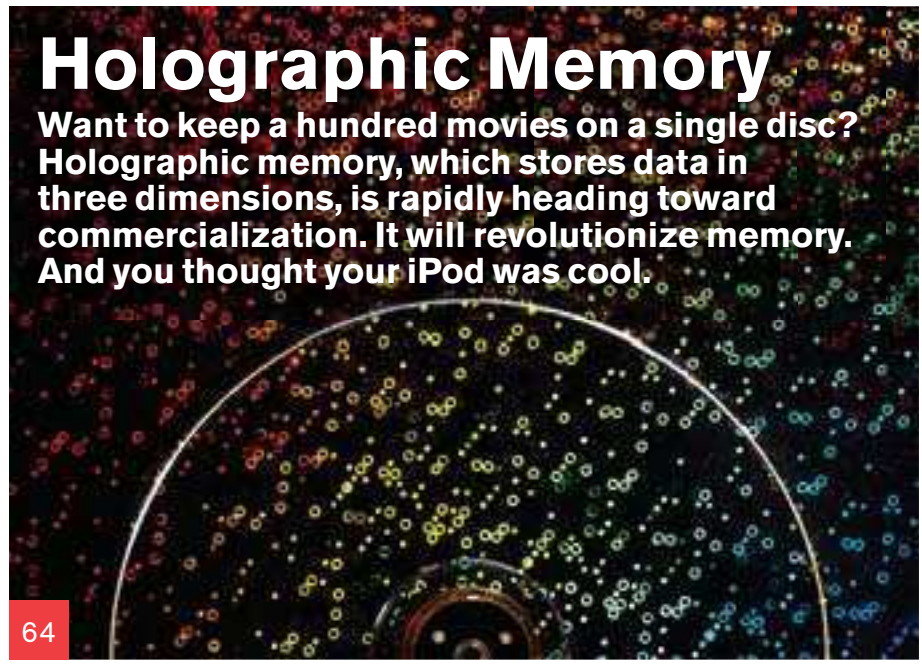

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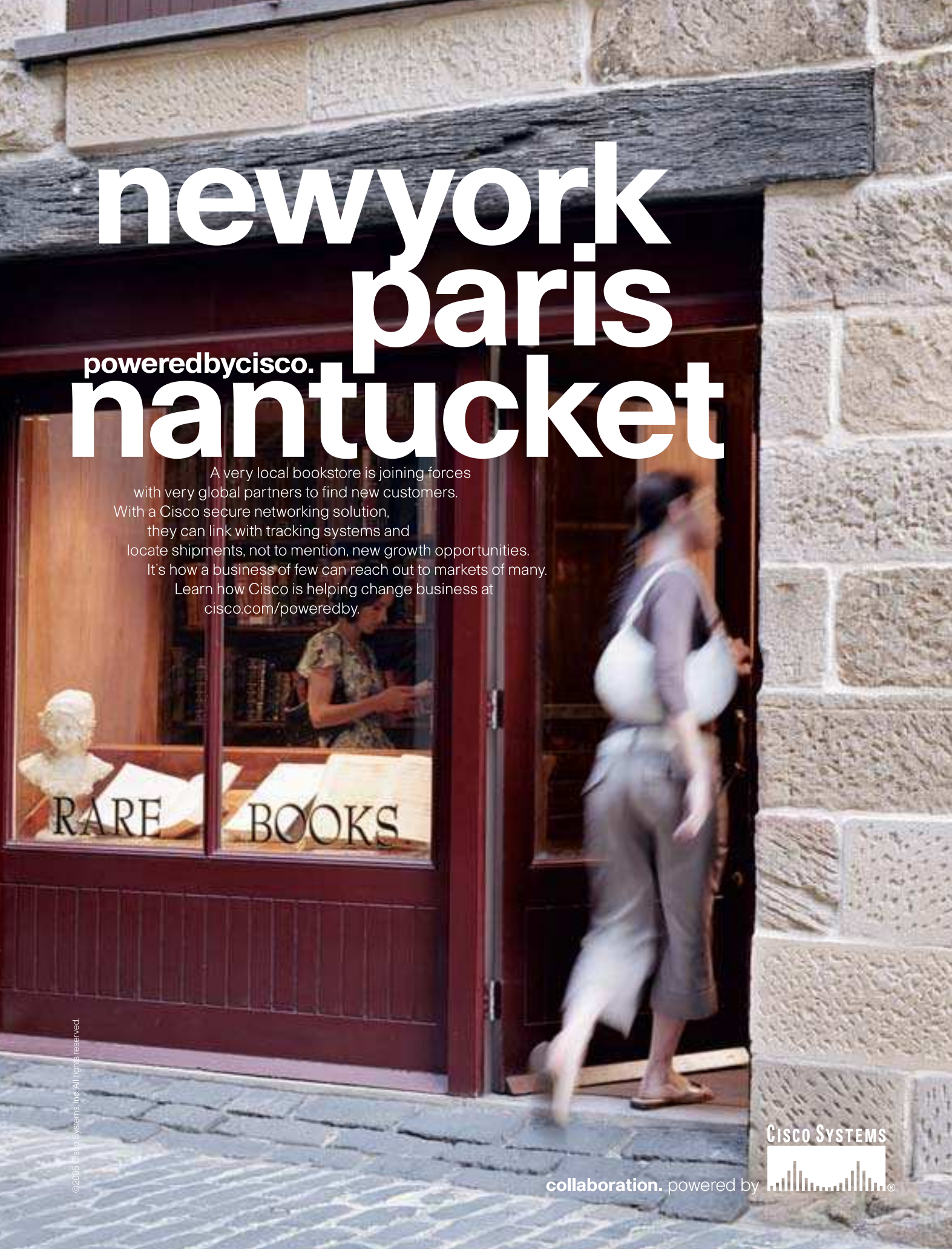
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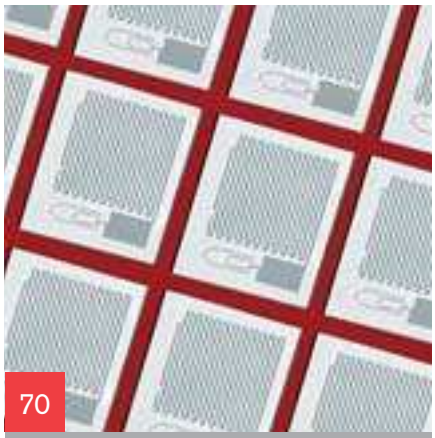

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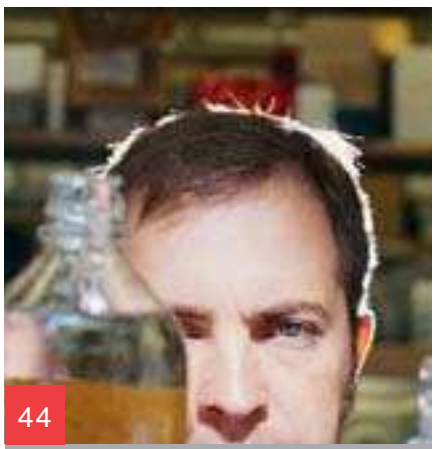

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FEATURE
Stem cell science on the shelf
Will it stay there?

What's new at technologyreview.com

It's all about directions this month online at *Technology Review*.

Cell phones with built-in location-finding technologies such as GPS are becoming almost as powerful as the dedicated GPS units used by prospectors, foresters, and outdoorsmen. For his review on page 79, *Technology Review* senior editor Wade Roush tested a few GPS phones on and off road. A photo-travelogue of his June 29 jaunt around San Francisco's Telegraph Hill, guided by a Nextel phone equipped with GPS and Trimble Outdoors' Adventure Planner software, starts at www.technologyreview.com/gps.

Roush isn't the only one looking for directions. The Web team is knee-deep in a redesign of the site, and, in the tradition of the open communication that helped set the architecture of the Internet, Web editor Brad King is having a conversation on his blog (king.trblogs.com) about new features and functionalities that should be a fundamental part of the new technologyreview.com. Visit the blog and let us know what you think.

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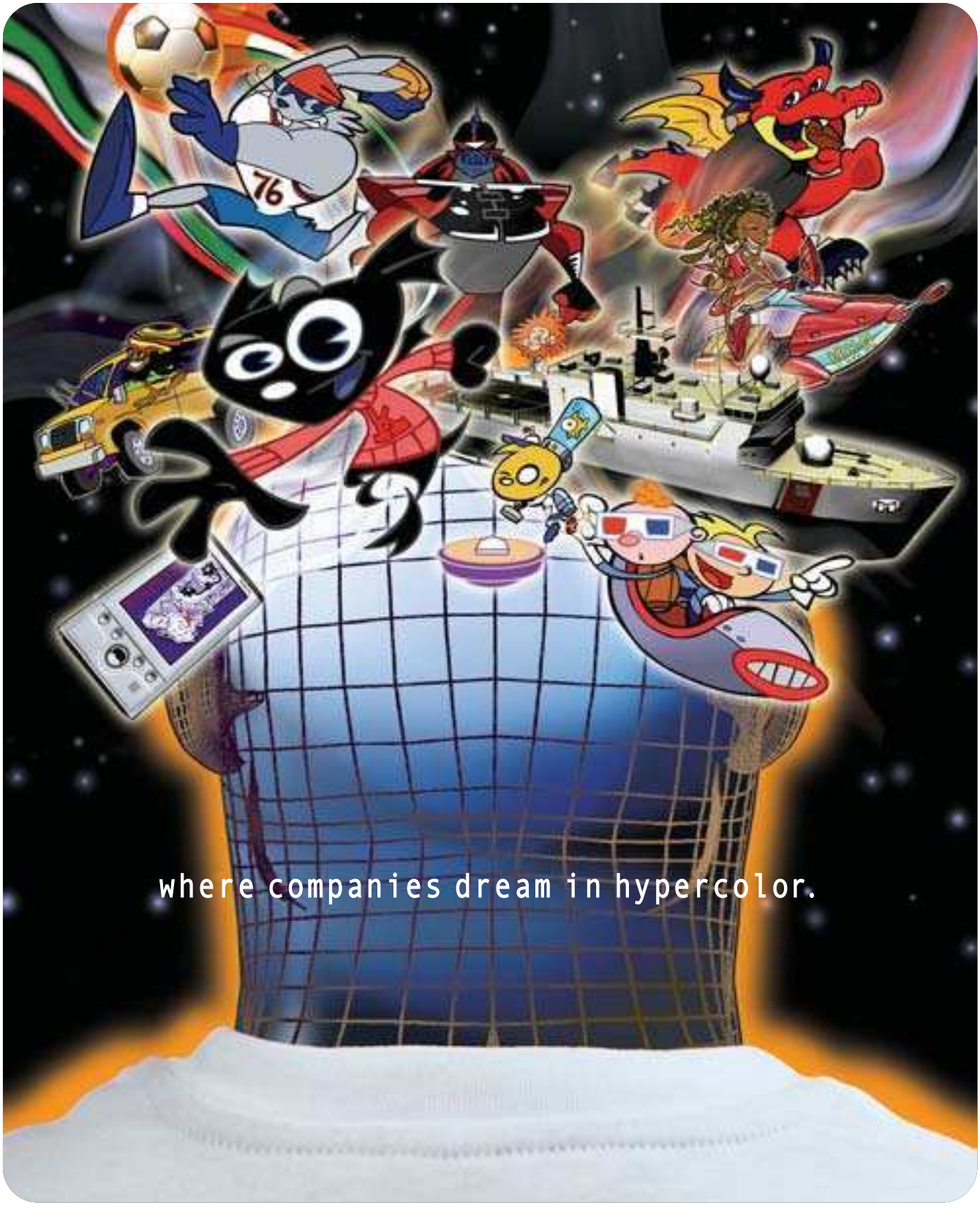

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Contributors

Roger Lowenstein, who wrote this month's review of Cisco's proposed method of accounting for employee stock options (see p. 76), has been writing since the mid-1990s about the debate over options accounting. This debate is crucial for tech companies, which are famous for their spirited use of options. Lowenstein says that while he sides with the accounting hawks, he thinks that "the financial and high-tech communities have got to get past their differences. Technology needs finance, and therefore investors, and therefore fair disclosure. But for the disclosure to be meaningful, it must have some measure of acceptance in Silicon Valley." Lowenstein is the author of *Buffett*, *When Genius Failed*, and *Origins of the Crash*. He contributes to the New York *Times* and other publications.

Charles C. Mann wrote "Braving Medicine's Frontier" (see p. 44), which explores the professional lives of stem cell scientists. He was inspired to do it, he says, because while he was writing other articles about stem cells, "people who were against stem cell research would say to me, 'I don't know what these guys are complaining about. All Bush said is that they can't use government money. If stem cells are so great, why don't they just get money from the private sector?' I thought this was an interesting question, and I decided to learn the answer." Mann's most recent book, *1491: New Revelations of the Americas before Columbus*, has received critical acclaim.

Ian H. Huchinson wrote this month's By Invitation column (see "Fusion Research: What about the U.S.?" p. 43). He is professor and head of the Department of Nuclear Science and Engineering at MIT; his major research interest is in plasma physics and controlled fusion. He and his team designed and built at MIT the Alcator C-Mod tokamak, a major national fusion research facility that he directed for its first 10 years of operation. "Fusion energy," he says, "may be the toughest science-and-technology challenge mankind has ever taken on. It is way more difficult than going to the moon."

Plamen Petkov, who photographed the holographic storage disc that appears on our cover, says, "I want that technology!" The clear disc, which is a prototype made by InPhase Technologies in partnership with Hitachi Maxell, holds 300 gigabytes of data—about as much as is stored on 60 DVDs. Petkov, a self-taught still-life photographer, shoots for *Harper's Bazaar*, *Newsweek*, and *Surface*.

J. D. SLOAN (MANN); NINA SUBIN (LOWENSTEIN)

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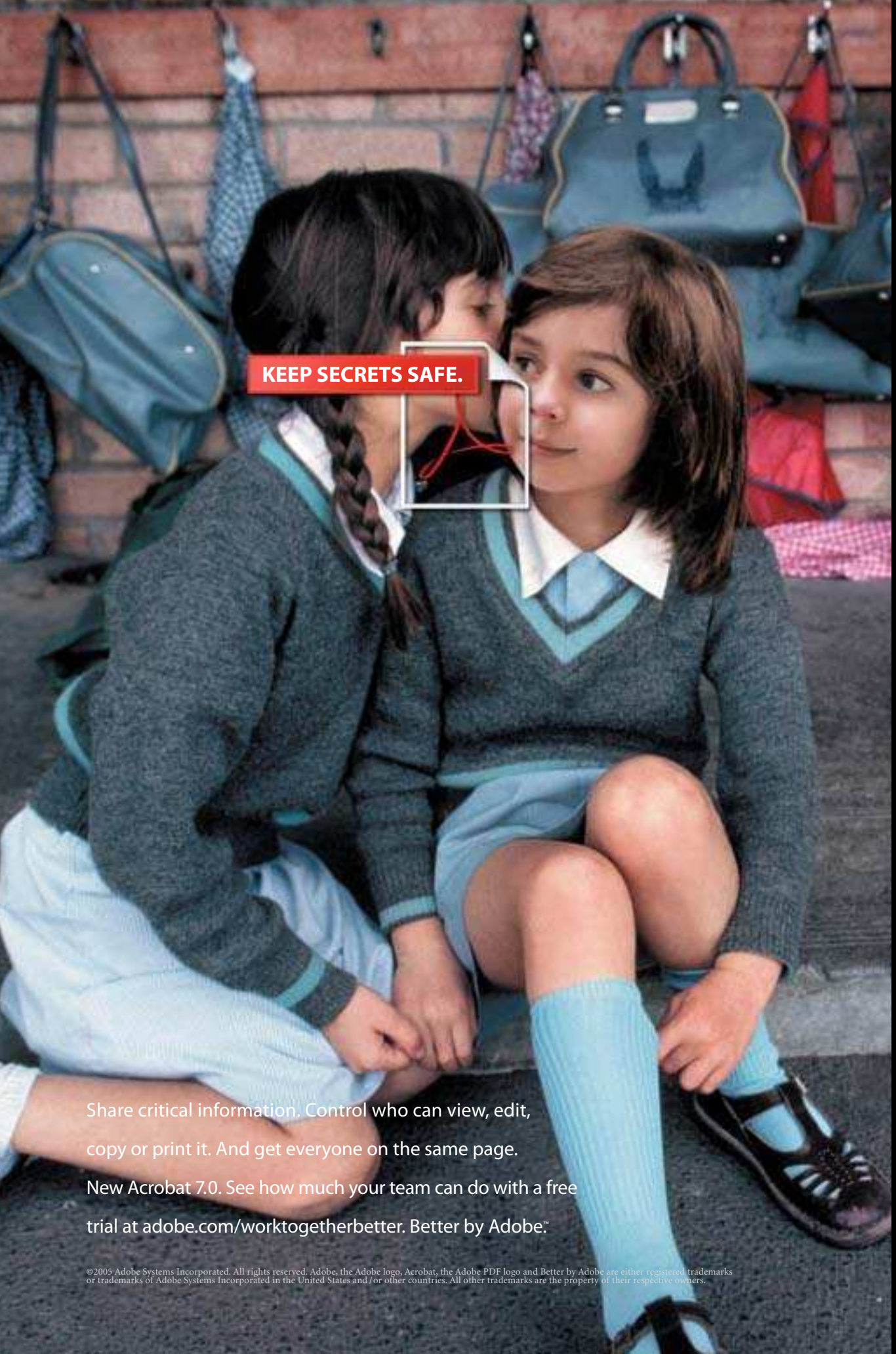

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Mesh Networking Matters

The benefits of any truly transformative technology are at first exaggerated, but their long-term effects surprise *everyone*. At the moment, mesh networks are experiencing such misvaluation. Their promoters (and they are many) now describe them with hyperbolic enthusiasm; but in the end they will be the mechanism by which machine intelligence becomes like electricity—that is, invisible and ubiquitous.

Mesh networks are not so very new: their conceptual lineage dates back to packet radio, a kind of digital data transmission used by amateur radio hackers in the 1970s. But investments in more reliable and intelligent networks made during the 1990s by the U.S. Department of Defense renewed interest in meshes; and within the last five years, academic institutions like MIT's Media Lab and startups like Aeria, BelAir Networks, Ember, MeshNetworks (now owned by Motorola), and Tropos Networks have rapidly advanced the technology. (Disclosure: Ember's chairman and acting chief executive, Bob Metcalfe, also serves on *Technology Review*'s board.) Meshies believe that mesh networks will overthrow traditional networking and communications and create entirely new kinds of distributed software.

For the purposes of this column, mesh networks (sometimes called mobile ad hoc networks, or MANETs) are local-area networks whose nodes communicate directly with each other through wireless connections. It is the lack of a hub-and-spoke structure that distinguishes a mesh network. Meshes do not need designated routers: instead, nodes serve as routers for each other. Thus, data packets are forwarded from node to node in a process that network technologists term "hopping."

Before dismissing mesh networks as being of interest only to specialists, consider their advantages over existing hub-and-spoke networks. Mesh networks are self-healing: if any node fails, another will take its place. They are anonymous: nodes can come and go as they will. They are pervasive: a mobile node rarely encounters dead spots, because other nodes route around objects that hinder communication. Meshes are cheap, efficient, and simple.

But they are still in development. The chief technical challenge for meshes is the inherent unreliability of wireless links. Because the unreliability compounds with each hop, the size of meshes is now limited. A related problem with hopping is that, for now, moving nodes seldom establish new connections "seamlessly": when a network's topology changes, some transmission paths can be temporarily disrupted. Therefore, voice and video sit unhappily on meshes. Meshes lack standards, too: low-bit-rate mesh networking has a standard called ZigBee that is supported by around 100 companies, including Motorola, Mitsubishi, Phillips, and Samsung, but high-bit-rate communications have no such standard (although the 802.11 committee of the Institute of Electrical and Electronics Engineers hopes to create one by next May).

What does all this mean? A few, early applications of mesh networks are already emerging. Meshes will allow municipalities to create cheap or free urban Wi-Fi networks (we will be writing about Philadelphia's effort in our November issue). Meshes have obvious advantages for military and security personnel who want networks that are unbreakable and "horizontal" *(see "Instant Networks," June 2005)*. Environmental scientists like meshes because they can provide continuous data from large geographical areas over many years *(see "Casting the Wireless Sensor Net," July/August 2003)*. But the most important application of meshes will be in what technologists once called "pervasive computing": embedding sensors and processors in things like clothes, electronics, and buildings and connecting them into smart networks.

Meshes will be the mechanism by which machine intelligence becomes like electricity: invisible and ubiquitous.

Mesh networks will be big business. There are billions of networked devices and embedded processors in the world; many more will be built. The best way to connect all of them will be through mesh networks. But the most disruptive business impact of meshes will be this: telecommunications companies do not own them. Meshes profoundly diminish the organizations that own and manage communications backbones.

But I believe that the most intriguing aspect of mesh networks is their cybernetic qualities. That is, mesh networks are adaptive systems that resemble biological systems (we recently wrote about MIT mathematics professor Norbert Wiener, the founder of cybernetics: see "Cybernought," June 2005). Many meshies like to say that they draw their inspiration from the behavior of swarming bees or ants. Some go even further. In "AntHocNet: An Adaptive Nature-Inspired Algorithm for Routing in Mobile Ad-Hoc Networks," published this year by the Dalle Molle Institute for Artificial Intelligence in Manno, Switzerland, Gianni di Caro and colleagues describe how ants from the same colony will converge to discover the shortest path from their nest to food; he proposes an algorithm for routing on mesh networks that explicitly imitates ant behavior. Ant colonies suggest how apparently intelligent behavior can emerge from a few fairly simple rules. Maybe mesh networks will promote new technologies that possess some of the properties of emergent intelligence?

Write and tell me at jason.pontin@technologyreview.com. ■


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Letters

Fading Memory

In his article ("The Fading Memory of the State," July 2005), David Talbot writes, "Saving the text of e-mail messages is technically easy; the challenge lies in managing a vast volume and saving only what's relevant. It's important, for example, to save the e-mails of major figures like cabinet members and White House personnel without also bequeathing to history trivial messages in which mid-level bureaucrats make lunch arrangements." Even assuming the existence of a politically neutral way to mark certain messages as unworthy of archiving, this seems like a really bad idea to me. Historians and archaeologists have extracted understanding of policy, culture, and daily life from such minutiae from ancient Mesopotamia forward. Those lunch arrangements could someday shed light on shifting alliances within a bureaucracy or a change in the status—as marked by the watering hole—of a bureaucrat. They could even offer a statistical test of the "late-night pizza" hypothesis about government war planning and other major policy initiatives. Even given the enormous volumes, it seems only sensible to keep as much data and metadata as possible, and to figure out how best to use and display it as it becomes of interest, rather than to circumscribe the archive before anyone even knows what uses future generations will make of it.

Paul Wallich
Montpelier, VT

I enjoyed David Talbot's article but was surprised that there was no mention of the ongoing court battles with the National Archives over electronic-record retention. As a District of Columbia resident, I have followed the occasional articles in the Washington *Post* about this litigation over the past decade or so. Exclusion of this aspect of federal electronic-record retention issues was a notable omission from what was otherwise an excellent piece.

Scott W. Langill
Washington, DC

Genetic Obesity?

It is plausible that obesity has some genetic roots ("Wired to Eat," July 2005). However, it is irresponsible to imply that the obesity epidemic in this country might, in any significant part, be related to genes. It is akin to walking into a room of smokers, discovering that a couple of them are genetically prone to lung cancer, and blaming the cancer on genes. It's very possible that some people are more prone to being obese, just as some are more prone to getting cancer. In a small percentage of people, these genes are probably more significant than environmental factors, and those people may have little control over their situation. But for most of us, eating healthy and exercising are enough to keep obesity in check. However, in a world where people will fight over a parking spot 50 feet closer to a store entrance, the news that obesity is caused by genes will simply be another excuse not to walk that extra 50 feet to McFatty's Hamburgers.

Jim Tierney
San Francisco, CA

Digital Properties

The debate about intellectual property ("Who Will Own Ideas?" June 2005) reminds me of the time when all inventions were owned by the English crown or by individual inventors in the United States. This distinction propelled the U.S. creativity force, to which some attribute the current world status of these two countries. Behind the invention surge is the entrepreneurial spirit—that is, the hope of financial reward. The work of *Star Wars: Revelations* is neither original, creative, nor financially risky. It is, rather, parasitical. It would not exist but for the work of others—work that cost a lot of money and carried a huge risk.

Jose F. Solis
Atlanta, GA

Pong Redux

Cell-phone games that detect motion ("Pong Redux," July 2005) are not the only gaming applications of that concept. There is a game by Nintendo that does much the same thing. Players of Nintendo's WarioWare Twisted control the action on the screen by tilting or turning a handheld console, due to motion sensors in the cartridge. In addition, IBM ThinkPads with motion sensors have been hacked so that the same concept can be used to play PC games and navigate the operating system.

Josh Jidov
Las Vegas, NV

Second-Mover Advantage

Jason Pontin's editorial raised the question about "second-mover advantage" ("The Rules of Innovation," May 2005). There is no question that this exists. Look at electricity: it was Tesla's later idea of AC power—not Edison's original DC technology—that prevailed. One can't easily predict which market will respond to technology or where the future leverage will be. Take maglev trains. This technology has been tried and rejected for economic reasons. For a new train technology to make economic sense, it must be compatible with existing tracks. Moreover, maglev has not proven to be anywhere near cost competitive with conventional steel rail. I guess the second-mover advantage goes to wheels and axles and to those who stuck with them and kept developing that technology.

Lloyd Weaver
Harpswell, ME

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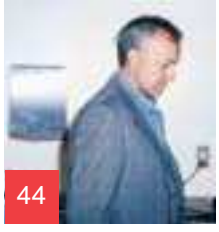
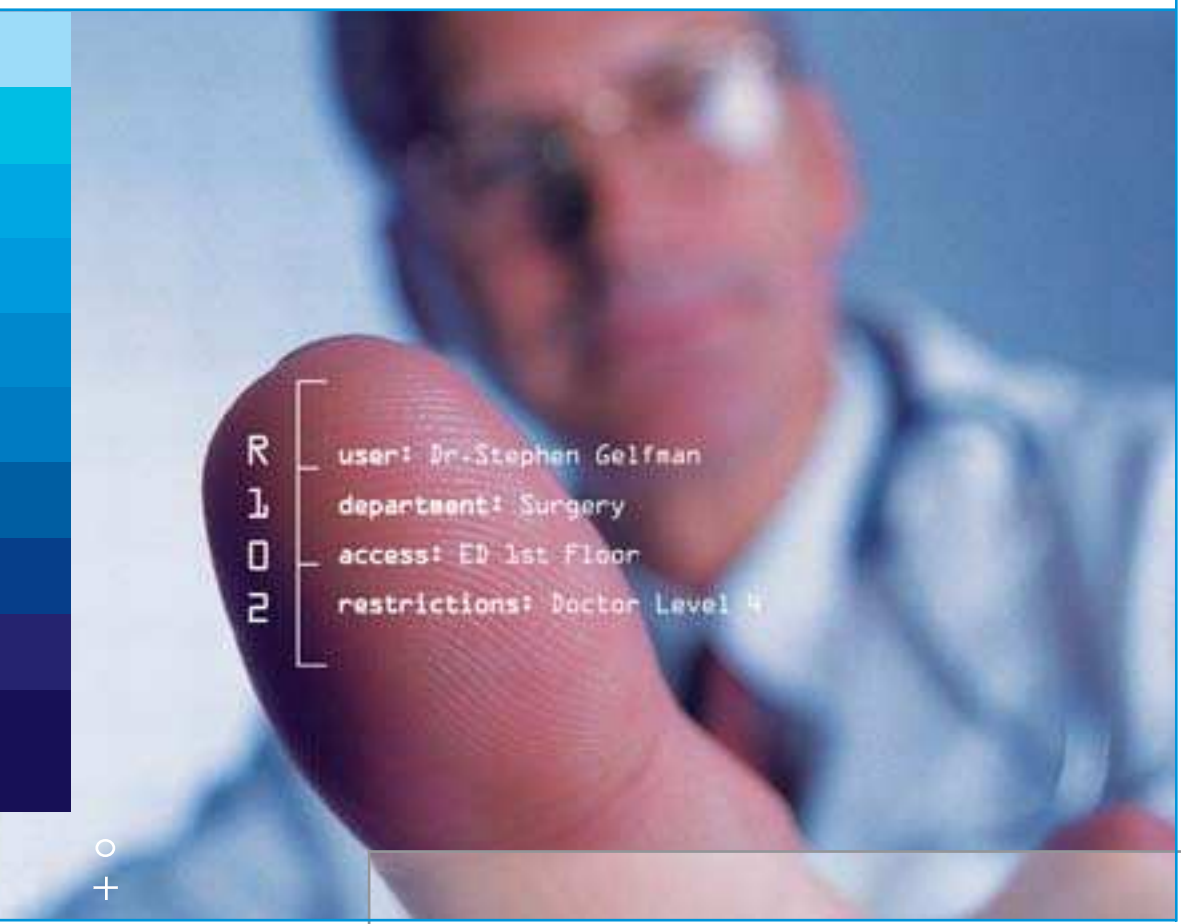
Let Stem Cell Science Live!



What does it mean to respect human life? That question is at the heart of the current debate swirling around research into human embryonic stem cells, and answering it is no easy task. George W. Bush's solution is a policy he announced in August 2001, based on the idea that each and every embryo is a life too precious to sacrifice for any cause. But that policy, which forbids federal funding of research involving any embryonic-stem-cell line created after President Bush's announcement, leaves some 400,000 embryos from in-vitro fertilization services (11,000 of which have already been donated for research) in frozen-storage limbo at U.S. fertility clinics. For many advocates of stem cell research, respect for life includes a profound belief that these embryos have the potential to unlock mysteries of illness and health, and of human life itself. On this view, each unused embryo represents an opportunity to treat and even cure a host of currently intractable ailments—paralysis, Parkinson's disease, cancer. For supporters of embryonic-stem-cell research, leaving such an opportunity on ice represents a sacrifice of something precious, and a failure to respect the lives of people suffering from such diseases.

It should come as no surprise that *Technology Review* favors advancing embryonic-stem-cell research. We've been rooting for stem cell science since 1998, when then associate editor Antonio Regalado first wrote about a small cadre of researchers struggling to isolate and cultivate embryonic stem cells. It was one of the first times that a mainstream publication had covered this emerging field, and as we worked on the piece, we wondered if the research might be too speculative to merit a cover story. We worried that publicity might endanger the field—even the researchers themselves—by drawing unwanted attention to it. But we never imagined, in the biotech-friendly Clinton years, that the biggest obstacle to embryonic-stem-cell science would be the U.S. government.

As contributing writer Charles C. Mann explains in "Braving Medicine's Frontier" *(p. 44)*, the Bush policy was not at first blush a terribly restrictive one. But the administration's policy turned out to be the central knot in what would become a horrific bureaucratic snarl. Four years later, U.S. stem cell researchers are still struggling to free themselves of the mess, while those in other countries, including South Korea, are pushing ahead. When *TR* went to press, a majority in the U.S. Congress was trying to pass legislation that would end the restrictions Bush imposed, Bush was promising to veto the bill, and proposed alternative measures were clouding the debate. Whether or not any of these bills becomes law, it's clearly time for legislative action that will permit U.S. stem cell science to thrive. ■



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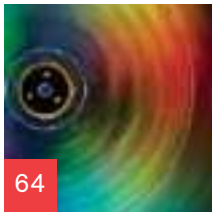


MEMORY

No Illusion

Holographic storage could create new microelectronics.

The rapid increase in the capacity of storage and memory technologies has had a remarkable impact on computing in recent years. Many of today's most popular consumer electronics are only possible because of the availability of cheap, high-density memory. Examples include iPods capable of holding up to 15,000 songs, flash memory cards in digital cameras that store hundreds of photos, and DVDs able to hold full-length movies with ease.

Storage technologies have for decades enjoyed their own version of Moore's Law. Moreover, the growth in storage capacity was driven by the simultaneous advancement of several different technologies, including magnetic hard drives and optical storage media such as CDs and DVDs. As *TR* senior writer Gregory T. Huang explains in this issue's cover story, "Holographic Memory," a new type of memory called holographic storage is on the verge of commercialization and is likely to continue—and perhaps even accelerate—these impressive advances. A holographic storage system writes data onto a polymer disc in three dimensions, dramatically boosting its ability to pack in the bytes.

The success of holographic storage is not guaranteed, of course. Like any new technology in the marketplace of microelectronics, it will face plenty of competition, both from the continual improvements in existing technologies and from other new forms of memory. There are other optical discs in development that store 100 gigabytes each, and IBM's experimental nanotech product Millipede has the potential to far surpass that capacity. But for most of us, the question of which technology will prevail is not nearly as interesting as the question of what changes are coming as a result of this enormous boost to computer memory. Starting on page 64, Huang explores some of the possibilities. ■

ENERGY

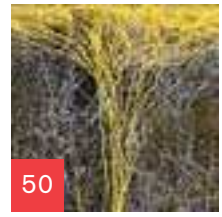
Nuclear Power?

Let's rethink this option, without losing sight of alternative energy.

Forget about nuclear winter; these days it feels like nuclear spring. Early signs point to a global renaissance in fission power. Twenty-four nuclear power plants are being built abroad. Well-organized U.S. utilities are identifying sites at existing nuclear power plants where new reactors might be built and asking the U.S. Congress to provide generous subsidies to help *(see "Nuclear Powers Up," p. 40)*. And all of this is happening without the kind of groundswell of public opposition to nuclear power witnessed in the 1970s and 1980s.

There is little question that nuclear power works well, produces no CO_2, and has a fairly safe record—Chernobyl excepted. The real issue is how best to spend public monies on energy production. The utilities say that new nuclear power plants will require federal help. Fair enough. But other approaches to weaning our thirst for fossil fuels will continue to require federal help, too—and they are equally promising.

A good case, for instance, can be made for advanced wind turbines. They are already economically competitive in regions that have strong winds and are convenient to the electrical grid, and with further subsidies they could be made competitive in more areas. Subsidies for hybrid cars would save oil. Even research on nuclear fusion has begun to gain momentum: an international consortium has agreed that southern France will host a $5 billion experimental fusion reactor, feeding hopes that the same process that keeps stars aflame will eventually light our cities at night *(see "Fusion Research: What about the U.S.?" p. 43)*. Fission reactors are an attractive option, but Congress and power generators should not consider them alone. ■



BASIC RESEARCH

Blue Skies Ahead

Corporate labs do well to indulge their inner visionaries.

The laser. The transistor. Optical fiber. All are transformational technologies that came into being not at academic labs or at startup companies, but at the research centers of large corporations—respectively, Hughes Aircraft, Bell Labs, and Corning Glass Works. In each case, a company allowed its researchers to be curious, to pursue projects that wouldn't add a dime to its bottom line in the next quarter, or the next year—or maybe ever.

But in the 1980s and '90s, corporate research became less curious, as managers pursued a "return on investment." Almost all of what now passes for corporate research consists of tweaking existing products rather than pursuing entirely new technologies. Fortunately, some companies are still thinking grandly—exploring areas of science and technology not immediately related to their existing sources of revenue. We profile three such "blue sky" projects on page 50: IBM's use of supercomputers to model the workings of the human brain; Intel's development of a way to detect individual biological molecules using lasers and Raman spectroscopy; and Bell Labs' methodical efforts to assemble a quantum computer that could one day solve certain types of computational problems millions of times faster than today's machines.

These efforts represent tiny slivers of much larger R&D enterprises. That's as it should be. But such farsighted work reminds us of the unique quality that corporate labs can bring to innovation. Technology giants like Intel, IBM, and Bell Labs, while tethered to the demands of the market, are still sometimes able to wander off in pursuit of technological adventure. ■

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Voices

"Search already is the spade by which we turn the soil of human knowledge. It's not 'the Web OS,' but it is our mainstream navigation interface."

John Battelle, founder of the *Industry Standard*, p. 81

"In the name of preserving morality, the president's decision has ended up creating moral anarchy."

Children's Hospital Boston researcher Mathew "Willy" Lensch, on President Bush's stem-cell policy, p. 46

"If one utility was to step out [and propose a nuclear plant], they could become the lightning rod for the antinuclear community, and for people's concerns on Wall Street."

Dan R. Keuter, Entergy's vice president for nuclear-business development, p. 40

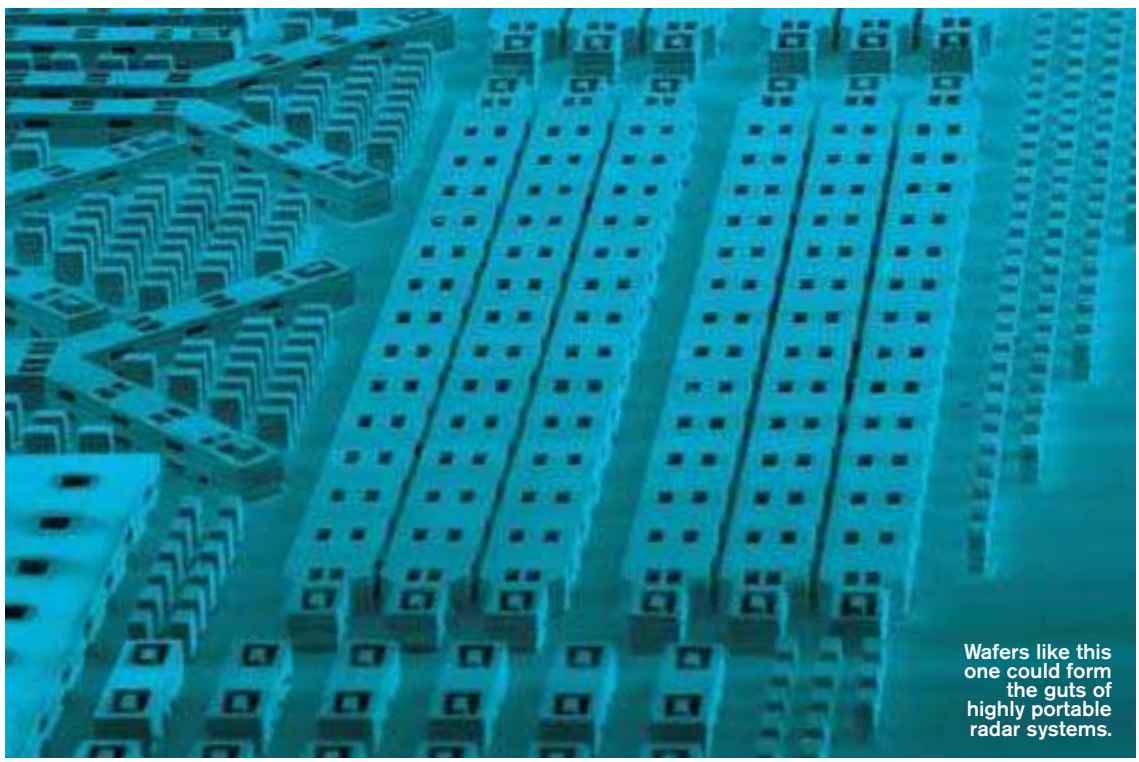
HARDWARE

Radio Communications

Fabrication tricks promise handheld radar

SECURE WIRELESS-COMMUNICATIONS systems and sophisticated radar have transformed warfare. But manufacturing them is costly and time consuming: the delicate radio components must be connected manually, increasing the systems' size and decreasing their reliability. In an effort to make such systems smaller, cheaper, and more dependable—for example, shrinking a TV-size military radio down to walkie-talkie size—military contractors are developing a sort of "circuit board" into which designers could simply plug radio components, much as engineers lay out chips on computers' familiar green motherboards.

Many radar and radio communications systems under development use millimeter-wavelength transmissions; such systems enable long-range communications and image resolution high enough to let soldiers easily discern whether a potential enemy is concealing a gun or bomb. While some millimeter-wave systems are already in use, they are too bulky and expensive for widespread deployment. "Ideally, you would like to be able to have things like a millimeter-wave radar on every Humvee," says Ezekiel Kruglick, a consultant for the U.S. Defense Advanced Research Projects Agency



Wafers like this one could form the guts of highly portable radar systems.

COURTESY OF MARIANNE MURPHY/BAE SYSTEMS

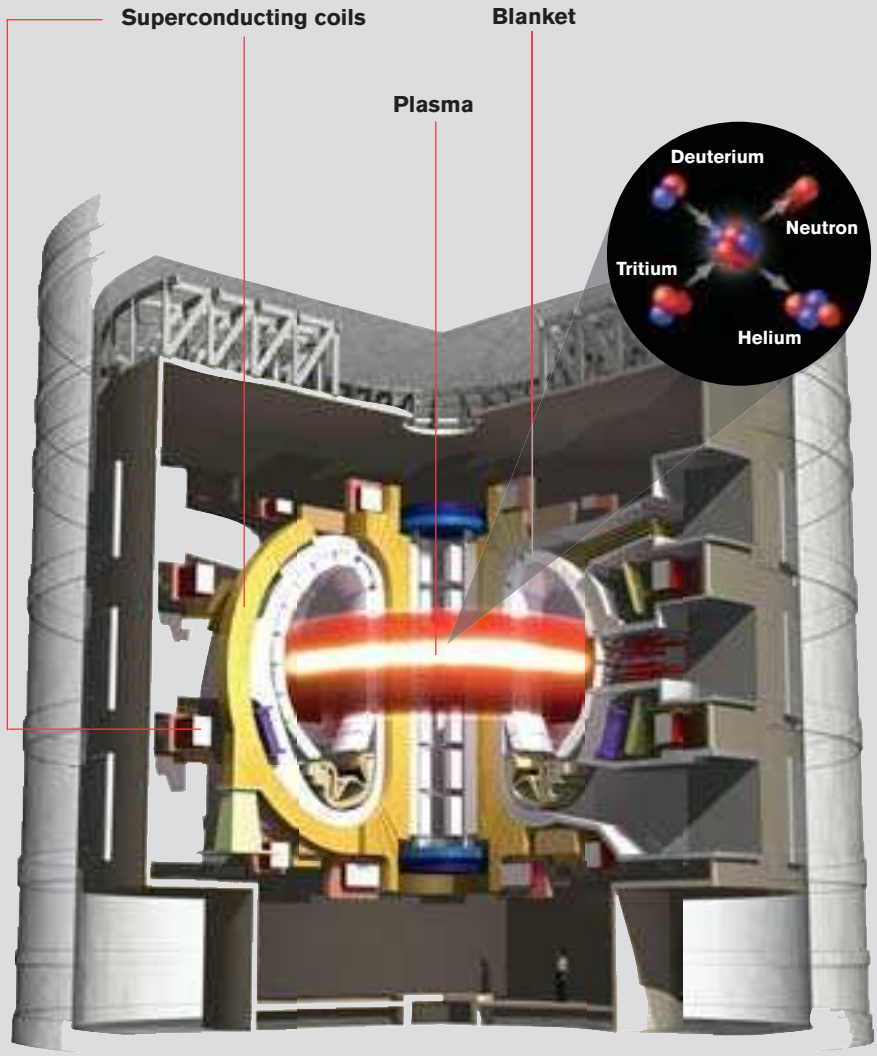
(DARPA). But routing the radio waves between the components of such a system requires custom-built channels or tubes. "Currently, [millimeter-wave] systems often look more like plumbing gone mad than high-tech electronics," says John D. Evans, a program manager for DARPA's Microsystems Technology Office.

As part of a DARPA project, BAE Systems and Rohm and Haas have developed a process that allows them to cheaply produce the radio frequency equivalents of circuit boards. The process uses a unique photoresist, a light-sensitive material similar to those used in semiconductor fabrication but 50 to 100 times as thick, to build the three-dimensional metal structures needed to connect millimeter-wave radio components. These circuit-board analogues are expected to decrease the size of radio and radar systems to one-twentieth of what they are today. They could also lower the cost of today's multimillion-dollar systems by as much as 99 percent and enable new applications, such as active defense systems that would calculate the trajectories of incoming mortar shells and launch countermeasures to intercept them.

"Currently, [millimeter-wave] systems often look more like plumbing gone mad than high-tech electronics."

Radio-frequency circuit boards could eventually work their way into a variety of consumer applications as well. They could, say, bring down the cost of active cruise-control systems, which can detect other cars and brake automatically. And the same manufacturing process could also allow the mass production of tiny vacuum electronic devices. These could enable, for instance, satellite-based TV and Internet access for moving vehicles.

BAE is on schedule to build demonstration systems using the new radio-frequency circuit boards by the end of 2007. Before the decade has ended, the technology could yield cutting-edge collision-avoidance radars, as well as high-bandwidth data, voice, and video satellite communications cheap enough for most cars. **Erika Jonietz**



ENERGY

Fusion Power

The International Thermonuclear Experimental Reactor (ITER)—which aims to prove the commercial viability of fusion power—is slated to be built in France by 2016. Here's how it will work.

Two hydrogen isotopes—deuterium and tritium—are heated in a doughnut-shaped chamber to more than 100 million °C, at which point they form a plasma, or ionized gas. Superconducting coils surrounding the chamber wall create a magnetic field that confines the plasma, forcing the deuterium and tritium nuclei to collide; when they do, they fuse to form helium nuclei, releasing neutrons. The mass of a helium nucleus and a neutron is less than that of a deuterium nucleus and a tritium nucleus; the excess mass is converted into a tremendous amount of energy, which is imparted to the helium nuclei and the neutrons. When the fast-moving neutrons hit the "blanket" that lines the chamber, they generate heat within it, which can be harnessed to produce electricity. Since there's no plentiful natural source of tritium, ITER will test ways of using some of the neutrons to create tritium from lithium-bearing materials in the blanket.

SOURCE: INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR

STARTUP

Designer Life

Codon Devices pioneers synthetic bio

LAST YEAR, some 250 engineers, computer scientists, and biologists gathered at MIT for the first conference in a new field called synthetic biology. Their common goal: designing and building from scratch artificial biological systems such as cells or microörganisms that can do anything from producing drugs to cleaning up pollution. But conference goers agreed that to achieve such a goal, they will need better tools for synthesizing the long stretches of DNA required to build the synthetic organisms' genomes.

Just a few months after the conference, some of the researchers founded a synthetic-biology startup called Codon Devices to provide those tools. With $13 million in venture capital funding, Codon is developing high-speed, low-cost DNA synthesis technology that could make synthetic biology a reality. By the end of this year, the company hopes to begin collaborating with academic researchers, helping them with DNA design and fabrication and delivering to them engineered DNA, proteins, or cells as products.

Codon's technology could enable improved protein-based therapeutics and vaccines. Since synthetic biologists engineer genomes from scratch, instead of modifying naturally occurring ones, they should be able to create proteins and cells with novel and complex capabilities. Synthetic biologists say they want to design and build genomes in the same way that electrical engineers make integrated circuits. "They've been doing large-scale integrated circuits since I was a kid. Now we're trying to do large-scale integrated biological circuits," says Harvard Medical School geneticist George Church, Codon's cofounder and chief scientific officer.

Although synthetic biologists can design DNA sequences for engineered organisms, they lack affordable tools that can quickly, automatically, and accurately turn those sequences into DNA molecules. With current methods, for instance, it can take many years, $10 million, and lots of manual handling and reagents to make a bacterial genome that is five million DNA letters long. And the process is prone to error: each letter of the final molecule has a 1 percent chance of being incorrect. Within the next two years, Codon's technology should reduce the time and cost of synthesizing DNA to about one-hundredth to one-thousandth of their current rates. That will enable the fabrication of longer stretches of DNA, says the company. And Codon aims to reduce the error rate to between one-thousandth and one-ten-thousandth of the current rate.

COMPANY: Codon Devices

HEADQUARTERS: Cambridge, MA

AMOUNT INVESTED: $13 million

LEAD INVESTOR: Flagship Ventures

KEY FOUNDERS: George Church, Joseph Jacobson, Drew Endy, Jay Keasling

TECHNOLOGY: Rapid, low-cost DNA synthesis for synthetic biology

Codon researchers use the basic approach of conventional DNA synthesis but have streamlined the process to cut down on the number of steps, the volume of reagents, and the manual transferring of reagents between containers—all of which allows for more automation. Key to the system is the use of a gene chip on which thousands of small fragments of the desired DNA sequence are synthesized in parallel in one step. The company's DNA-design software determines how to parcel out the sequence so that once the fragments are synthesized they can be pieced together with minimal labor.

The startup will face technical hurdles. For one, it may be difficult for Codon's gene chip–based synthesis technology to handle certain types of sequences, such as very repetitive ones, says John Mulligan, CEO of Blue Heron Biotechnology, a Bothell, WA, gene synthesis company that is also looking to use gene chips.

And there are business challenges as well. Codon is the first startup to try to commercialize synthetic biology. "It may take a little while to shake out the business models," says Mulligan. But the startup is right to focus on selling its DNA design capabilities, rather than just its DNA synthesis services, he says. "That's where the high value is."

Corie Lok

Prototype

JOHN MACNEILL (FUSION); COURTESY OF ARTHUR PEASE/SIEMENS (POST-ITS)

Virtual Post-Its

With new software developed at Siemens Corporate Technology in Munich, users of Global Positioning System–equipped cell phones and handheld computers may soon be able to leave each other virtual post-it notes. The Siemens system could do everything from helping highway department personnel label pothole locations for road crews to allowing a city's residents to craft personalized guides for visiting friends. A user of the software can leave a note in a particular location by sending a message from that spot on his or her wireless device. The system transmits the message, along with the GPS coördinates of the location, to a server. When the intended recipient (who must also have a GPS-enabled wireless device) comes within a preset radius of those coördinates, the server delivers the message. Siemens expects to license or commercialize the technology in about two years.

Touchy-Feely Screen

Touch screens greet tourists at museums, shoppers at checkouts, and even drivers on dashboards. In spite of the name "touch," though, they don't feel like much—just flat, boring glass or plastic. But press a virtual button on a screen from San Jose, CA's Immersion, and you'll feel the same satisfying clack you'd feel pushing a key on a keyboard. The

COMPUTING

Microsoft's Emissary in Japan

Katsushi Ikeuchi wants to change our relationship with computers

THE EXQUISITELY WROUGHT Buddha at Nara, the most important Buddhist statue in Japan, fills the field of view. Next comes a 13th-century temple at Bayon, Cambodia, with its 50 stone towers, each adorned with four carved faces. The pictures appear in startling detail on the 150-degree parabolic screen, bringing viewers up close and personal with the real sites. But there's a twist: the scenes don't show the way things *are*; they show the way they were hundreds of years ago, when these masterpieces were built. The Nara Buddha has been reconstructed twice after being damaged by fires, and Bayon has endured ages of decay. But through a painstaking process of image capture, integration, and rendering, their original splendor has been restored.

Yokoso ("welcome" in Japanese) to Katsushi Ikeuchi's Digital Archive Project, which seeks to digitally reconstruct and preserve for posterity the original states of Buddhist and Hindu carvings and other artifacts throughout Asia. The project is housed in an ultramodern lab building—the elevators here talk—at the University of Tokyo's Institute of Industrial Science.

Ikeuchi, who taught for 11 years at Carnegie Mellon University (CMU) before joining Japan's top academic institution, is renowned in academic circles for his efforts to transform the way people interact with the world via computers. Beyond the archive project, he is the architect of dexterous humanoid robots that learn tasks by observing people, as well as

JEREMY SUTTON-HIBBERT

Katsushi Ikeuchi says digital studies of ancient artifacts capture "tangible heritage."

COURTESY OF ELIZABETH CONRADY/A&R PARTNERS

an innovator in intelligent-highway research—projects that have made him a force in computer vision, robotics, and virtual reality.

This summer, Microsoft tapped Ikeuchi to direct its new Institute for Japanese Academic Research Collaboration. Ikeuchi will serve as Microsoft's main connection to Japanese computer science, helping identify and fund research collaborations in robotics, wireless applications, graphics, and other areas that the company hopes will keep it on top of the world of computing.

Ikeuchi's knowledge of East and West—and, in particular, of Microsoft—makes him a natural selection for the job, Microsoft officials say. At CMU, he mentored Harry Shum, now head of Microsoft Research Asia in Beijing, to which the new institute will report. Until recently, Ikeuchi served on the Beijing lab's technical advisory board. Microsoft already supports work in Japanese universities. But, says Ikeuchi, that work has been selected piecemeal. The institute, he says, seeks "to make that coherent" and in the process help Microsoft, Japan—and just about everybody else. "Technical results propagate through oral communications, not formal presentations," Ikeuchi says. "Unfortunately, Japanese researchers have few personal contacts with Western researchers. If we can connect Japanese researchers with Microsoft Research Asia people tightly, from this, [their work] will propagate worldwide."

Microsoft kicked off the institute by funding projects with three of Ikeuchi's University of Tokyo colleagues, in graphics, user interfaces, and natural-language processing. The company declined to disclose funding terms. But while its research organization supports hundreds of university collaborations worldwide, Shum says, the institute, forging ties with the academic community of a single nation, marks a first for Microsoft. "If we look at this region, Japan certainly deserves some special attention," he says. "Now we put all these programs under this umbrella."

Ikeuchi, who will retain his University of Tokyo position, will return to Cambodia this December to add finer detail to his Bayon temple model. And earlier this year, the salt-and-pepper-haired scientist took a different tack on preserving the past—by building a robot that employed visual sensors and object- and task-recognition algorithms to study a human performer and learn a traditional Japanese festival dance called *Aizu bandaisan odori*. In contrast to his Buddha studies, which capture what Ikeuchi likes to call "tangible heritage," this is an effort to preserve "intangible heritage," he says.

"Unfortunately, Japanese researchers have few personal contacts with Western researchers."

But it's transforming the future, not reconstructing the past, that Ikeuchi hopes will be his greatest legacy. His intelligent-highway work is linked to a Japanese government effort to develop a transportation system that will route cars more efficiently to minimize congestion and reduce pollution. It's also intended to make time spent on Japan's crowded highways more productive, partly by giving commuters in-car Internet access. Human-computer interaction and computer vision systems will be essential to this infrastructure, which will recognize driving behaviors and warn of impending collisions, he says.

But all this is just an appetizer for Ikeuchi's ultimate goal: combining legions of service robots with an intelligent infrastructure that will free an aging population in Japan and elsewhere from mundane tasks like driving, cleaning, and cooking, helping people preserve their independence. As the population grows older, says Ikeuchi, "we will definitely need some intelligent environment or service environment to support elderly people."

Robert Buderi

Prototype continued from p. 25

device works by tricking your sense of touch. Precise motors vibrate the top layer of the display. The vibration varies depending on which graphic you touch—a car's thermostat, say, or its radio tuner—creating a distinct sensation for each. An on-screen visual response and an audible click or buzz add to an illusion that overrides your perception of the display's hard surface. Immersion is currently licensing the technology and shipping demonstration models to automakers, display manufacturers, and other companies.

Low-Power Data

Some gadget lovers read the news on the fly using small displays such as watches equipped with Microsoft's Smart Personal Object Technology (SPOT). But the devices, which pick up wireless "datacasts" with updates on traffic, stocks, sports, and the like, must be recharged every couple of days—which limits their appeal to mainstream consumers. Now a battery-sparing innovation could enable datacast receivers to go longer between charges. Pablo Rodriguez of Microsoft Research and Julian Chesterfield of the University of Cambridge realized that if some of the information in a datacast is unchanged from the previous download—say, for instance, it's still 35 degrees and sunny—it's a waste of power to download it again. They created a system that precedes each update with a highly compressed signature

TELECOM

Music Dial Tone

Venture capitalist Fred Wilson cofounded Flatiron Partners, one of the spark plugs for New York's late-1990s "Silicon Alley." Now a partner in Union Square Ventures, he blogs on venture capital and new media.

How do you see the future of music shaping up?
All the pieces are basically there for what I call "music dial tone." Once it's all together, for less than $5 a month, you'll have access to the entire library of recorded music, from any place and any time. By the end of this decade, it will be the dominant way people consume music.

What's the revolution?
The revolution is the business model. Most telecom services now charge a flat fee per month. When music goes this way too, consumers will start to expect all media to be delivered this way. TV and film—other than first-run movies in the theaters—will be next.

You've got an investment in high-definition radio—why will anyone want that?
My iPod has been an eye-opening experience. I have thousands of songs on it, but I am listening mostly to podcasts [homemade, downloadable, MP3-format radio programs]. Why? Because I want someone to program my iPod. When we have music dial tone, we will still want someone to program it for us. That's what radio does. Radio execs already understand this. They just need us to build the digital platform—and by that I mean music dial tone—and they'll provide the programming and monetize it.

Spencer Reiss

Fred Wilson looks forward to a world where all music is available on tap.

STARTUP

Robotic Rehab

Chicago PT wants to help stroke survivors learn to walk again

700,000 PEOPLE in the United States have strokes each year, and almost a third of those who survive lose the ability to walk on their own. The good news is that physical therapy can help many regain lost abilities and even walk again. The bad news is that government and private insurers have recently cut support for therapy. From 1994 to 2001, the duration of rehabilitation stays for stroke survivors decreased by a third, and Joel Stein, chief medical officer of Boston's Spaulding Rehabilitation Hospital, says this trend continues. A prototype robot built by Evanston, IL, startup Chicago PT may speed up patients' progress, allowing more of them to walk before the window for therapy closes.

The robot was designed to help therapists resolve a conundrum. A therapist's first priority is safety, but especially in the case of reteaching a patient to walk, safety can get in the way of progress. Walking requires throwing yourself off balance with one leg and catching yourself with the other; making mistakes in the process and adapting to them is an important part of encouraging a stroke victim's brain to rewire itself around its injury. But such mistakes can be dangerous for some stroke survivors. According to Chicago PT cofounder Dave Brown, a physical therapist and professor at Northwestern University, since therapists don't want their patients to get hurt—and don't want to injure themselves in attempts to catch them—they err on the side of ensuring that patients don't fall.

Chicago PT's robot allows patients to make mistakes safely. The wheeled machine uses arms and a harness to give patients different degrees of support and guidance as their ability to walk improves. At first the robot might support all of a patient's weight and slowly move straight forward, while the therapist rides along in a wheeled chair, guiding the patient's legs through walking motions. Freed from having to support patients, therapists can "be really intelligent with their hands rather than being just a clamp to keep a person from falling over," according to Brown.

As patients get stronger and more coördinated, a therapist can program the robot to let them bear more weight and move more freely in different directions, walking, kicking a ball, or even lunging to the side to catch one. The robot can follow the patient's lead as effortlessly as a ballroom dancer, its presence nearly unde-

continued on p. 31

A robotic aid frees a physical therapist to use her hands more intelligently.

COMPANY: Chicago PT

HEADQUARTERS: Evanston, IL

AMOUNT INVESTED: $1.85 million

LEAD INVESTORS: Rehabilitation Institute of Chicago, National Institute of Standards and Technology

KEY FOUNDERS: Edward Colgate, Michael Peshkin, David Brown

TECHNOLOGY: Robots for rehabilitation

EVAN KAFKA (MUSIC); COURTESY OF MICHAEL PESHKIN (REHAB); COURTESY OF REN NG (FOCUS)

Prototype continued from p. 27

or "hash" of each of its components. If a device finds data with a matching hash in its memory, it doesn't bother to download that component. In experiments, the system reduced download times by 40 percent—meaning wireless watches would use less juice.

Fail-Proof Focus

Tired of blurry photographs? Ren Ng, a computer science graduate student at Stanford University, has developed a digital camera and software that allow photographers to refocus images after they have been taken. The trick lies in a 296-by-296 array of 125-micrometer-wide lenses placed between the main lens of the camera and the image sensor. In effect, the array divides incoming light from a single shot into multiple images—each captured from a slightly different angle—that are all recorded at the same time by different regions of the camera's image sensor. Software then allows the user to digitally refocus the resulting image at different depths—to pick up a person otherwise lost in the background, for instance. The limitation of the technique is that the refocused images are relatively low resolution, since the pixels of the camera's image sensor are divvied up to register multiple perspectives. While this is currently a barrier to widespread commercialization, Ng expects refocusability to be the next killer app in photography, as cameras' pixel density continues to increase.

Dick Swanson still holds traditional silicon solar cells in high regard.

ENERGY

Solar Sunny Days

Solar modules are selling like hotcakes

Solar energy is finally getting its day in the sun, buoyed by renewable-energy incentives and snowballing economies of scale. Former Stanford University professor Dick Swanson, the founder and CTO of Sunnyvale, CA–based SunPower, says there's still an important place for the industry's incumbent technology: crystalline silicon.

Sharp, GE, Sanyo—you've got some very big competitors. Is that intimidating?
Of course it is. This industry is maturing fast, and it's going to be harder and harder to keep up if you don't have the resources to grow with the market. There's also a new wave of more aggressive entrepreneurial companies like Q-Cells in Germany. Thanks to a very aggressive incentives program, it's now the world's biggest solar market.

Is traditional silicon technology losing ground to thin-film and other new nanosolar technologies?
There's been a common belief in the solar industry that growing silicon crystals and then cutting them up with a saw is just hopelessly expensive. Most people are surprised silicon lasted as long as it has. But for the next ten years at least, it looks like silicon is going to continue to dominate, if only because of all the new capacity coming online.

How much further can you push silicon's efficiency?
Today's standard commercial module converts about 12 percent of the sun's energy into electricity. The record in a laboratory is 24.9 percent, so there's plenty of room for improvement. Our highest-performing commercial module today is 18 percent efficient, meaning roughly 50 percent more power for a given area than the industry standard. We've been able to put all the electrical contacts on the back of the cell, which eliminates what's known as shading.

Why do buyers settle for less efficient cells?
For now, anybody that has anything that even looks like a solar module can sell it. We're all running our lines flat out, and buyers take what they can get. But higher efficiency means we can charge a premium per watt. For a remote telecom site where you have to helicopter everything in, obviously the less material you need to achieve your rated power the better. On a suburban rooftop, that matters less.

But it does matter?
Absolutely. Roof space is finite. Installation costs are pretty well fixed. So ultimately the only way to be more cost effective will be to squeeze more electricity out of your panels.

Government incentives are clearly still a key element.
We still need them, but not necessarily for very long, and especially not in places with high retail electricity prices and a lot of sun. The industry's current momentum should drive things to about half the cost of where we are right now. That will open up new markets, which will drive costs even lower. But it's a step-by-step process. **Spencer Reiss**

TIMOTHY ARCHIBALD

continued from p. 29

tectable until it senses the patient starting to drop and quickly stops a fall. In the later stages of physical therapy, the robot can nudge patients off balance to help them learn to recover.

Brown and Michael Peshkin and Ed Colgate—both colleagues of Brown's at Northwestern—founded Chicago PT in 2003, using seed money from the Rehabilitation Institute of Chicago and the National Institute of Standards and Technology's Advanced Technology Program. The company's hands-on system marked a departure in the growing field of rehabilitation robotics. Previously, rehab robots mainly assisted patients in the performance of repetitive exercises, with little therapist involvement. A device available since 2001 from Hocoma of Volketswil, Switzerland, for example, suspends patients over a treadmill and uses a robotic exoskeleton to move their legs through walking motions.

The earliest clinical trials of any rehabilitative robot involved an arm therapy robot developed at MIT by a group led by mechanical engineers Neville Hogan and Hermano Krebs. Using sensors embedded in their robot, the researchers have since 1994 gathered data about the progress of more than 250 patients. Their first results showed that "the patients who were doing the robot training improved twice as much" as those who were undergoing nonrobotic therapies, according to Krebs.

A hospital gets the same reimbursement for a therapist's time whether the therapist is using a robot or a rubber band.

Chicago PT will need to demonstrate that its more hands-on approach is also effective. The company is entering a critical phase, during which it aims to place robots in multiple hospitals and possibly a model clinic where therapists, engineers, and patients will collaborate on design improvements and simplifications.

In the short term, Chicago PT will need to demonstrate that the robot works and win the support of major therapeutic centers. In the long term, its success, and that of other companies developing rehab robots, will likely depend on changing the reimbursement landscape. Currently, a hospital gets the same reimbursement for a therapist's time whether the therapist is using a "robot or a rubber band," Brown says.

In addition to proving its machine works and getting funding, Chicago PT will have to brace itself for competition as more and more groups develop robots for walking therapy. The MIT group, for instance, recently unveiled one robot that aids stroke victims with ankle therapy and is working on another that more closely resembles Chicago PT's. **Kevin Bullis**

20 years ago in *Technology Review*

From "The Medical Promise of Personal Magnetism"
(August/September 1985, p. 72)

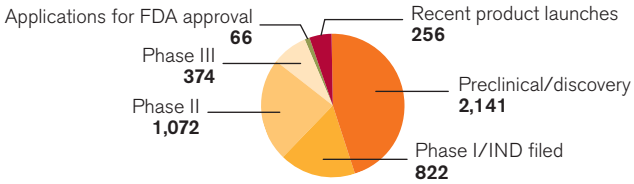
The key to measuring the brain's magnetic field is a cryogenic sensor known as the SQUID. It is most effective when used in a magnetically shielded room, such as the one at M.I.T.
(Photo: David Cohen)

Treating Cancer

Cancer is the second-leading cause of death in the United States, surpassed only by heart disease. But recent technological developments offer the hope of new and better ways to combat the disease. For many of the most pervasive types of cancer, about half of the drug candidates furthest along in the research pipeline use approaches other than that of traditional cytotoxic drugs, which work by killing cells or preventing their division. With continuing advances in the development of therapies like monoclonal antibodies and tumor vaccines, biotechnology should account for a growing portion of the cancer drug market, which may reach $80 billion a year by 2009. As costs soar and reimbursement wanes, though, many patients are unlikely to reap the benefits of some of the most promising of these developments. **Stacy Lawrence**

U.S. cancer research pipeline by stage

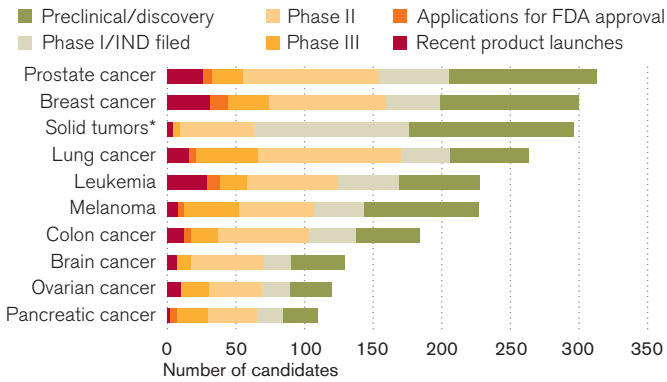
Almost 5,000 cancer drugs are currently being researched or have recently been released.



SOURCE: BIOPHARM INSIGHT

U.S. cancer treatment research pipeline

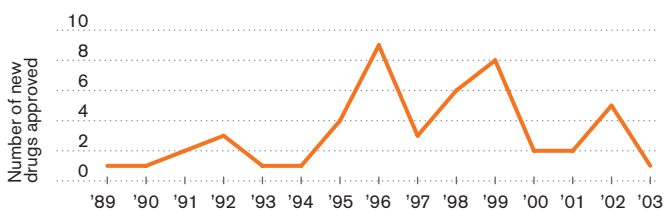
Drugs for prostate and breast cancer treatment dominate the development process.



*A CANCER THAT ORIGINATES IN AN ORGAN OR IN TISSUE OTHER THAN BONE MARROW OR THE LYMPH SYSTEM. CHART DOES NOT INCLUDE THE MORE THAN 1,600 CLINICAL RESEARCH CANDIDATES GENERALLY TARGETED AT CANCER. SOURCE: BIOPHARM INSIGHT

Approval of new cancer drugs drops

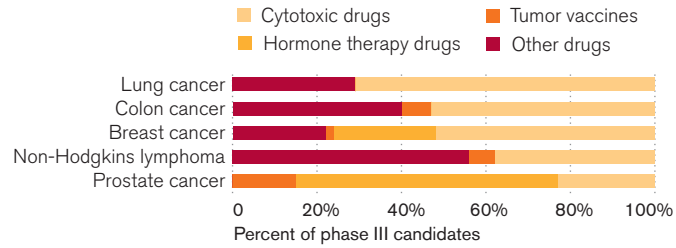
U.S. Food and Drug Administration approval of novel treatments based on new molecules peaked in the mid- and late 1990s.



SOURCE: U.S. FOOD AND DRUG ADMINISTRATION

New drug strategies

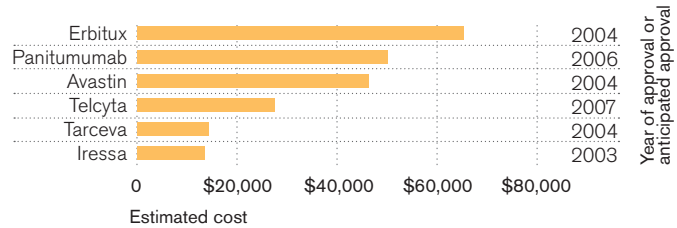
Alternatives to cytotoxic drugs represent at least half of the candidates in the most advanced stage of testing for three major types of cancer.



SOURCE: DZ BANK, WWW.CLINICALTRIALS.GOV

Cost of cancer drugs

A 24-week course of the newest cancer treatments can cost more than $65,000.

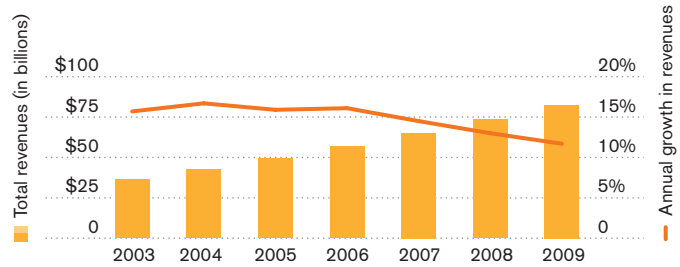


DATA ARE ESTIMATES FOR 2005 OR EARLIEST YEAR IN WHICH THE DRUG IS ESTIMATED TO BE COMMERCIALLY AVAILABLE, AND ARE FOR A 24-WEEK COURSE TREATING NON-SMALL-CELL LUNG CANCER. PANITUMUMAB ESTIMATE IS FOR COLORECTAL CANCER.

SOURCE: CREDIT SUISSE FIRST BOSTON

Global cancer drug therapy revenues*

The market for cancer drugs is expected to double by the end of the decade.



*MANUFACTURER REVENUES. SOURCE: KALORAMA INFORMATION

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Funding of Innovative Startups

Company	Founded	CEO	Recent funding	Key investors	Technology	Prospects
Osiris Therapeutics	1992 Baltimore, MD	C. Randal Mills	$50 million	Friedli Corporate Finance (investors in most recent round undisclosed)	Adult-stem-cell therapies for repairing tissue damage from heart attacks, knee injuries, and graft-versus-host disease, a condition affecting bone marrow transplant patients	**By focusing its research on adult-stem-cell therapies, Osiris has been able to avoid the controversy surrounding embryonic stem cells. Products are on the way.**
PicoChip	2000 Bath, England	Guillaume d'Eyssautier	$20.5 million	Intel Capital, Rothschild, Scottish Equity Partners, Pond Venture Partners, and Atlas Ventures	Reconfigurable digital-signal-processing chips for multiple wireless standards, including WiMax	**PicoChip has a strong foothold in WiMax with its initial products. It could be riding the next wireless wave.**
RF Code	1997 Mesa, AZ	Armando Viteri	$20 million	QuestMark Partners and Intel Capital	RFID tags, readers, sensors, and software for analysis and mining of data	**The market for RFID is expanding rapidly. RF Code's software could play a critical role.**
RelayHealth (formerly Healinx)	1999 Emeryville, CA	Giovanni Colella	$7 million	McKesson, Cisco Systems, Venrock Associates, U.S. Venture Partners, Conning Capital Partners, SI Ventures, and Lilly Ventures	Web tools to help patients using an online service for consultation, prescription, and renewal	**The benefits of allowing tech-savvy patients to use Web tools to help manage their health care are obvious. The market is wide open for RelayHealth.**
DriveCam	1998 San Diego, CA	Bruce Moeller	$18 million	Menlo Ventures and JMI Equity	Video equipment used in commercial trucks; when the system detects unsafe driving, it saves the corresponding video footage, which can be downloaded to a computer for a manager to review	**DriveCam says its system reduces trucking companies' liability and their exposure to insurance claims. As a result, it already boasts an impressive client roster.**
Miasolé	2001 San Jose, CA	David Pearce	$16 million	Kleiner, Perkins, Caufield, and Byers	Solar cells manufactured on rolls of flexible material	**Several other startups are pursuing new solar technologies, and it's too soon to determine which, if any, will win out.**
Cardiva Medical	2002 Mountain View, CA	Augustine Lien	$8.3 million	Stockton Partners, Sycamore Ventures, Harbinger VC, and W. I. Harper Group	A device that seals off femoral-artery puncture sites following vascular catheterization	**Millions of catheterizations are done annually; Cardiva, whose product was approved by the FDA last year, is targeting this market.**

Will take time to reach market **Strong competitive position** **High-benefit, high-risk technology**

Company Spotlight

Miasolé Several solar startups with innovative new technologies, including Nanosolar and Konarka, have recently received venture-capital funding. Miasolé is looking to make solar power cost-effective by using thin-film manufacturing techniques, avoiding the expensive processing that silicon-based solar cells require.

Miasolé enjoys great buzz thanks to a $16 million investment from the superstar VC firm Kleiner, Perkins. However, its competitor Nanosolar has also recently raised $20 million. It remains to be seen whether these new types of solar cells are generating investments based on the general promise of cleaner energy or whether they are commercially feasible technologies able to compete with existing and well-entrenched silicon-based photovoltaics.

Osiris Therapeutics Amid all the debate over embryonic-stem-cell research, Osiris Therapeutics has been advancing the development of adult-stem-cell therapies. By using stem cells extracted from the bone marrow of living adults, Osiris has dodged the criticism that it is unethical to harvest cells from embryos.

Some Osiris products are already undergoing human tests. The first treatment for bone marrow transplant complications in leukemia patients is in phase II clinical trials and is the only stem-cell product with U.S. Food and Drug Administration fast-track status, according to Osiris. Two other products are also ready for human trials. One, designed to heal heart muscle damage in heart-attack patients, is in phase I clinical trials, and another, which will help repair knee tissue, recently won FDA approval to begin clinical trials.

While it is generally accepted by scientists that embryonic stem cells will have broader therapeutic applications, adult stem cells could also play a valuable role in repairing some types of tissue, and Osiris's approach seems to be working. The company believes that, if all goes according to plan, its first therapeutic product may be available by 2007. **Andrew P. Madden**

And the Rich Get Richer

Energy investors get great stock performances—plus cash!

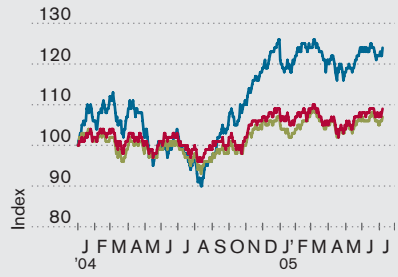
The *TR* Large-Cap 100 and Small-Cap 50 indices live online, where they are updated daily. Visit www.technologyreview.com/trindex.

Oh, to have foreseen this spike in oil prices and to have dumped all our money into energy stocks. More precisely, to have realized that when everyone thought the easy money had already been made, there were still some pretty easy returns sitting right there on the table. Energy stocks again led our large-cap index, in the month ending July 8, and were outpaced in the small-cap index solely by biotechnology issues. The only mystery to us is the continuing dismal performance of First Calgary Petroleums—a stock that's become almost comical in its ability to act as a contrary indicator to its own sector.

So what are these lucky energy companies doing with all their newfound cash? Interestingly enough, they're putting it aside for a rainy day. According to Arnie Berman, analyst at Creditsights, energy companies in the S&P 500 saved 15 cents of every dollar in the past year—a rate five times as high as the average company's. Berman suggests that the smart money in the sector (i.e., its executive suite) either doesn't think the high prices will endure, has limited confidence in its own long-term growth prospects, sees few opportunities to spend that money wisely, or all the above. The good news for investors: in lieu of drilling too many new holes, these companies have been giving that money back to shareholders in the form of dividends, share repurchases, and debt payments.

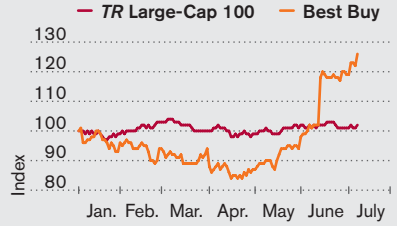
The broader market has held up even as oil prices have shrugged off gravity. The S&P 500 barely outpaced the *TR* Large-Cap 100 in notching a 1.1 percent gain through July 8, and our small-cap index was not far behind. All three indices are in the black for the past 12 months, with small stocks showing a 24.9 percent gain. **Duff McDonald**

TR stock index comparison



	% change 6/10–7/8	One-year % change
TR Large-Cap 100	1.1%	8.7%
TR Small-Cap 50	0.7%	24.9%
S&P 500	1.1%	9.3%

In depth: Best Buy



How many ways can you sell an iPod? Best Buy seems to have an idea or two: in its most recent quarter, ending May 28, it saw an 11.6 percent year-over-year increase in revenue. The big-box retailer shocked Wall Street with a profit of 51 cents a share in the quarter—a lot more than analysts' expectations of 30 cents—on the strength of sales of digital TVs, games, and, yes, MP3 players. The shares are up 26 percent in 2005 alone.

TR Large-Cap 100

	% change 6/10–7/8	Total market cap (millions)
Energy	5.4%	1,325,094.7
Software and services	1.3%	489,389.7
Telecommunication services	0.7%	753,391.6
Computers	0.6%	729,220.8
Semiconductors and equipment	0.2%	408,041.8
Consumer	-0.4%	183,482.2
Biotechnology and pharmaceuticals	-1.3%	1,180,504.5
Aerospace and defense	-1.3%	238,396.1
Health care	-1.4%	204,789.7
Media	-1.7%	447,029.6

TR Small-Cap 50

	% change 6/10–7/8	Total market cap (millions)
Biotechnology and pharmaceuticals	6.6%	12,680.5
Energy	4.8%	12,122.4
Media	4.2%	14,016.2
Telecommunication services	3.4%	3,432.2
Consumer	3.1%	2,845.2
Health care	2.6%	10,354.0
Semiconductors and equipment	0.8%	5,948.1
Computers	-0.9%	19,786.1
Aerospace and defense	-1.3%	2,242.7
Software and services	-2.3%	16,377.7

TR Large-Cap 100, top gainers

	% change 6/10–7/8	One-year % change
Symantec (Nasdaq: SYMC)	73.4%	6.9%
Best Buy (NYSE: BBY)	23.4%	49.2%
France Telecom (NYSE: FTE)	19.8%	15.9%

TR Small-Cap 50, top gainers

	% change 6/10–7/8	One-year % change
Protein Design Labs (Nasdaq: PDLI)	15.6%	18.6%
T&F Information (London: TFI)	15.0%	0.5%
Affymetrix (Nasdaq: AFFX)	14.7%	92.7%

TR Large-Cap 100, top losers

	% change 6/10–7/8	One-year % change
Biomet (Nasdaq: BMET)	-9.7%	-29.5%
Walt Disney (NYSE: DIS)	-9.4%	2.7%
Guidant (NYSE: GDT)	-7.7%	26.2%

TR Small-Cap 50, top losers

	% change 6/10–7/8	One-year % change
First Calgary Petroleums (Toronto: FCP)	-14.1%	-34.9%
Taylor Nelson (London: TNN)	-8.3%	-0.4%
Macromedia (Nasdaq: MACR)	-8.3%	75.5%

NOTE: IN THE *TR* SMALL-CAP 50, FMC TECHNOLOGIES HAS REPLACED UNITED DEFENSE INDUSTRIES, WHICH WAS ACQUIRED BY BAE SYSTEMS ON JUNE 24. SOURCES: STANDARD AND POOR'S CUSTOM INDEX SERVICES, *TECHNOLOGY REVIEW*, YAHOO FINANCE

The Starving Actor

THE CASE: Since TiVo launched in 1997, it has been consistently applauded. The company name is used by consumers as a verb (to "TiVo" a show is to record it for later viewing), and customer satisfaction is off the charts. But TiVo has never generated a profit nor come close to winning the number of customers it originally expected. The company is now on the brink of profitability—but is also highly vulnerable.

THE STORY OF TIVO is a made-for-TV drama—and a good one. Few corporate histories better illustrate the fact that companies can make groundbreaking products but fail to make money. In its eight years, TiVo has struggled with a fundamental weakness: to build its customer base, it has had to cede its customer relationships to its partners. That flaw has made TiVo vulnerable to the vicissitudes of the fast-changing market for broadcast media.

That wasn't supposed to be the way the story went. After the company formed in 1997, its then president, Mike Ramsay, claimed that TiVo "is changing the paradigm of television." TiVo gives subscribers the ability to save television programs to digital video recorders (DVRs) for later viewing. It also does other clever things, such as recommending shows to subscribers based on their viewing behavior.

By the summer of 2000, despite slower-than-anticipated retail and Internet sales, TiVo seemed to have the cable and media relationships in place to sell millions of its DVRs. Cox Communications, NBC, Disney, and CBS had all invested in the company, and satellite broadcaster DirecTV and cable company Comcast had agreed to distribute TiVo DVRs to their customers.

Skip ahead to 2005. The company is still losing money, and the partner that is fueling most of its growth—DirecTV—will soon promote a service that will compete with TiVo. What happened?

TiVo

FY 2005 revenues: $172 million
Employees: 228
Number of subscribers: 3.3 million

Going It Alone

When it started in 1997, TiVo (whose officers declined to be interviewed for this story) saw an opportunity to make the experience of watching TV as controllable and personal as the experience of using a PC. This was possible largely because of the rapid improvement of storage technology: hard drives that could record hours of video were becoming affordable. Also, advances in data compression algorithms made it possible to capture video streams in real time.

TiVo's product was a VCR-sized box that could continually capture an incoming television signal, enabling users to pause and rewind live broadcasts. The box allowed users to schedule recording in advance by selecting programs from an on-screen guide and could even record all upcoming episodes of a given show.

TiVo's user interface for managing recorded programs set it apart from early competitor ReplayTV, which now has less than one-third of TiVo's market share. "People who got a TiVo were extremely pleased with it," says Josh Bernoff, an analyst with Forrester Research.

Word of mouth helped to increase TiVo subscriptions by 86 percent between 1999 and 2000, but according to Bernoff, that may have been in spite of TiVo's marketing strategy. In 2000, when the fledgling company had revenue of $3.6 million, it spent more than $150 million on advertising and sales and ran a television ad that featured network television executives being thrown out windows. "This angered the networks with whom TiVo was trying to partner but did not help consumers understand what the TiVo did," says Bernoff.

TiVo had a hard time convincing consumers that they should pay $9.95 per month—after purchasing the recording device—to watch content that they were already receiving anyway, adds Adi Kishore, a senior analyst with the Yankee Group. Weak sales of TiVo boxes surprised many. In 2000, Forrester Research forecast that by 2005, 53 million homes would have DVRs. According to analysis firm Magna Global, just 1.2 million DVR subscriptions were sold in the first quarter of 2005.

In 1999 and 2000, despite its small audience, TiVo signed up several network partners and advertisers—including NBC, HBO, Starz Encore, and Showtime—to offer interactive, enhanced programming and advertising through TiVo boxes. But this didn't do much to move the needle. By the end of 2000, TiVo had fewer than 150,000 subscribers. It needed another way to get customers.

The Initial Search for Partnerships

In July 2000, Comcast agreed to a trial in which it offered TiVo boxes to its subscribers in Cherry Hill, NJ. TiVo was hoping that the trial would lead to a deal in which Comcast would integrate TiVo software into its set-top boxes. But Comcast balked. According to Kishore, the main reason for the impasse was that TiVo wanted direct access to viewers, which Comcast was unwilling to concede. This access, TiVo knew, was of enormous value: through its DVRs, TiVo gathers data about viewing habits—such as whether viewers skip over a given ad or watch it repeatedly—and sells that information to advertisers. But without the kind of demographic details that TiVo collects from its direct customers, its

data isn't as enticing. TiVo wanted to own the subscriptions and simply give Comcast a percentage of the subscriber revenue. But Comcast wouldn't budge, says Kishore.

In April 2001, when the initial trial with Comcast had failed to lead to a larger deal, TiVo decided to reduce the amount of cash it was burning through. The company laid off approximately 25 percent of its staff, which allowed it to avoid seeking additional funding.

TiVo's next hope for a cable deal was dashed by a cruel twist of fate. In November 2001, AT&T Broadband agreed to offer TiVo DVRs to its customers in New England, Colorado, and Silicon Valley, but within a few weeks, Comcast acquired the cable provider and its 14 million customers, killing the deal.

Without a cable partnership, TiVo felt it had to continue selling DVRs through retail channels—which it didn't really want to do. The company prospectus filed with the SEC before TiVo went public in the fall of 1999 stated that "our current plan is to stop selling personal video recorders." The company had hoped to make its money by selling its software to cable and satellite companies.

TiVo still sells its DVRs at stores like Best Buy, Circuit City, and Costco, and via its website. According to research firm Magna Global, between the end of 2001 and the first half of 2005, TiVo subscriptions recruited by this means increased from 235,000 to more than 1.1 million.

But while TiVo initially failed to gain a cable partner, it succeeded, in 2000, in partnering with DirecTV. In fact, the majority of TiVo's subscriptions to date have come from this relationship. Of the satellite broadcast giant's 14.4 million customers, more than two million use TiVo.

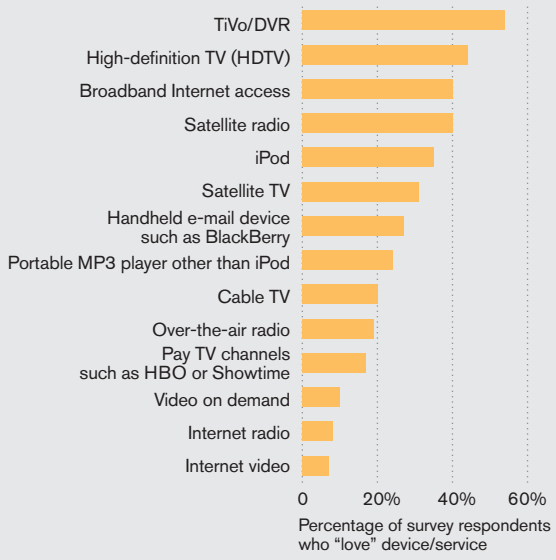
The deal went through for a couple of reasons. First, when TiVo began talks with DirecTV, the satellite provider already had a DVR service through its partnership with Microsoft's UltimateTV, according to Brian Wieser, vice president of Magna Global. That gave DirecTV more leverage when it insisted on controlling TiVo's relationship with subscribers. "I'm not sure [TiVo] would have agreed to the same deal at the same price" if it weren't for the presence of an entrenched competitor, Wieser says.

The deal was also made simpler by a technological difference between cable and satellite. It has been easier, says Wieser, for satellite broadcasters to roll out new technologies such as the DVR because they can make software changes in a central location. Cable operators have different equipment in different areas, so they have to deploy technology gradually.

TiVo's partnership with DirecTV has been fruitful. Since the end of 2001, subscriptions to TiVo's service through DirecTV have increased from 230,000 to 2.1 million, and represent more than half of all DVR subscriptions through satellite services. But as we will see, DirecTV may soon cease to offer TiVo significant growth.

Customers Love Their TiVo

A new survey quantifies owners' oft-proclaimed "love" for their TiVo/DVR devices.



SOURCE: ARBITRON/EDISON MEDIA RESEARCH

A New Partnership in a Newly Troubling Market

While TiVo was nurturing its relationship with DirecTV, other companies in the business of television were making life harder for TiVo. Most worryingly, cable operators began to develop their own DVRs. In 2002, the first cable boxes with DVRs arrived, produced by set-top box makers Scientific-Atlanta and Motorola.

TiVo responded in April 2003 by hiring Marty Yudkovitz as president. Yudkovitz had been an executive vice president at NBC and seemed to have the experience necessary to understand the cable industry, having helped to build the CNBC and MSNBC channels, as well as the MSNBC.com website. Yudkovitz's tenure would be short lived, as he would leave the company in January 2005. But within weeks of his departure, the long-sought deal with Comcast was done. In March 2005, TiVo announced that it will develop software for Comcast's DVR platform.

This time around, TiVo has relented on the issue of who owns the customer. It has agreed that Comcast will manage the relationship with consumers and will pay TiVo a monthly fee for each subscriber using one of Comcast's DVRs. In turn, Comcast has agreed to market TiVo service to its 21 million subscribers, although fewer than half of them—8.8 million—have digital cable, which is required to run TiVo on Comcast DVRs.

Beyond the matter of customer control, Comcast has another reason to like this deal. The company can use TiVo to entice current analog subscribers to upgrade to digital subscriptions, which cost between $10 and $15 more per month. What's more, when Comcast converts a customer to digital, it can offer additional premium channels, as well as movies and sports programming on demand.

Being used to lure customers away from analog cable service could prove uncomfortable for TiVo, which currently markets its products to analog customers. As of July, TiVo was advising analog users—who represent 61 percent of all cable subscribers—to get the most from their existing cable packages. "You need more time, not more channels," the company said on its website. (That admonition no longer appears on the site.)

The deal is a bit awkward for both parties, but it could help TiVo become what it has always wanted to be: a software provider. "The Comcast deal looks great on paper," says Magna Global's Wieser. But by waiting so long to partner, TiVo may have missed a golden opportunity. Offering its DVRs to Comcast customers in 2000 might have sparked greater demand for the devices. Instead, it was nearly two years be-

fore Time Warner Cable became the first cable company to deliver DVR service.

Still, the Comcast deal gives TiVo the chance to gain millions of new subscribers. It also improves the company's chances of earning advertising revenues. From the beginning, TiVo expected that high-quality, long-form ads (which customers would *choose* to watch) would provide a substantial proportion of its revenues. While TiVo advertisers have included NBC, HBO, and Fox, as well as Coca-Cola, Chrysler, and Royal Caribbean, the company could not previously deliver the millions of viewers sought by advertisers. In an April 2005 SEC filing, TiVo stated that revenues from advertising, while increasing, were "not material."

But if TiVo can continue to expand its audience, it will make sense as an ad platform, claims Wieser. "They are the clear leader in advertising" among DVRs, he says. TiVo is developing an ad management system that Comcast can deploy not only with TiVo's DVRs but also with those made by Motorola and Scientific-Atlanta.

But while TiVo would love to increase revenues through ad sales, its success will ultimately hinge on its ability to differentiate itself in an increasingly crowded field. According to Magna Global, 2.3 million cable subscribers now use DVRs not developed by TiVo. The total DVR market is expected to grow by more than 260 percent between the beginning of 2004 and the end of 2005, to nearly 12 million units.

TiVo has reason to think that it can grab a good share of any new group of DVR users. No company has yet been able to match TiVo's recording features, such as the Season Pass, which records all episodes of a program, and the WishList, which finds all programs featuring a particular actor or director. Nor has anyone designed a more user-friendly interface. TiVo also has some good old-fashioned legal defense of its market: it has received 85 domestic and foreign patents, including several related to unique aspects of its user interface. It has another 117 patents pending.

To preserve its advantage, TiVo will need to not only offer a product with better features than its competitors' but also do so in the midst of the transition from analog to digital television. This shift could prove dangerous for TiVo. Digital-cable providers may soon begin to compete with TiVo by creating DVR services that do not require programs to be downloaded onto cable boxes. According to Wieser, Time Warner Cable has tested a network DVR service that enables viewers to rewind, pause, and fast-forward television shows by storing copies of them on its servers.

Later this year, Time Warner Cable will test a modified version of the service called Startover, which will enable viewers who tune in late to a program to watch it from the beginning. Cable companies are pursuing networked DVRs because they are more cost effective than DVR cable boxes, which typically wear out after three years, Wieser says.

But TiVo's woes don't end with competitor DVRs from the cable industry, or with digital cable's pursuit of robust, networked, non-TiVo software. The company may no longer be able to rely on DirecTV for subscription growth.

In April 2003, News Corporation purchased 68 percent of Hughes Electronics, the parent company of DirecTV. The following January, DirecTV announced that its next generation of DVRs would use software from a News Corporation company, NDS Group. DirecTV receivers with NDS DVR technology are set to ship this fall.

The new DirecTV DVR service will include unique features such as the ability to jump to a specific scene in a program, as well as to pay for any downloaded pay-per-view movies only when they are viewed, says Robert Mercer, DirecTV's director of public relations. DirecTV will continue to sell DVRs with TiVo technology, says Mercer, "but our marketing efforts will focus on the new DirecTV boxes."

Watching TiVo's Performance

Increased subscription and service revenues coupled with a decreased reliance on hardware sales have helped TiVo's market showing this year—but the stock continues to underperform.

SOURCE: REVERE RESEARCH

Opportunities beyond TV?

In June, TiVo installed Tom Rogers, former president of NBC Cable, as its president and CEO. Rogers has been on TiVo's board since 1999 and oversaw NBC's investment in the company. In a press release, he laid out two priorities for TiVo: to broaden its reach through its distribution channels, and to improve advertising revenues. Shortly after Rogers took over, TiVo launched software that allows subscribers to use their TiVo remote controls to request, while watching an ad, that information from the advertiser be sent to them.

Perhaps sensing that its partnerships may not be enough to ensure profitability, TiVo is beginning to look beyond television. This year the company signed several licensing agreements that will allow Internet content to be stored on its DVRs. In January, it announced the creation of Tahiti, a software platform that will provide tools for developers to create applications for sharing content such as music and videos between PCs and TiVo DVRs.

TiVo has also updated its DVR to enable content to be transferred to portable video players. The company has licensed this TiVoToGo software to chip maker AMD, digital-media software company Sonic Solutions, and Microsoft, to enable video playback on devices using Microsoft's Portable Media Center, on Pocket PCs, and on smart phones.

Licensing its technology to third parties "is the best business model for TiVo," believes the Yankee Group's Kishore. The TiVo brand, which is so well regarded because of the user-friendly TiVo interface, could serve to differentiate consumer electronics devices that control multimedia content. Such arrangements would allow TiVo to avoid the hardware business and focus on creating innovative software.

TiVo is on the cusp of profitability. In the first quarter of 2005 it narrowed its losses to less than $1 million and upped its subscriber base by 10 percent, to 3.3 million. This represents a year-over-year doubling of its subscriber base. These are good signs. Stay tuned. **John Gartner**

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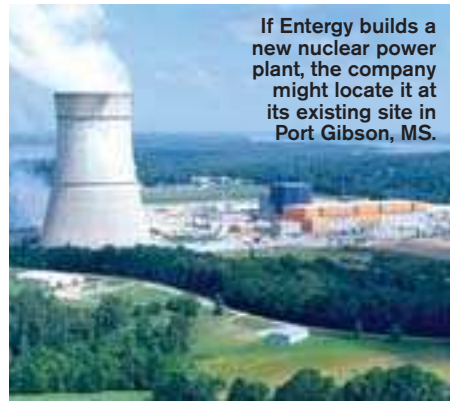
Nuclear Powers Up

THE CASE: Improved nuclear-power technologies are at hand—but the public is still wary. Entergy Nuclear decided that before proposing a new plant, it should band together with other utilities, lobby for subsidies, and make the link between nuclear power and the "hydrogen economy."

THE U.S. NUCLEAR-POWER industry has been stagnant for three decades; the last successfully completed reactor order was made back in the early 1970s. The 1979 Three Mile Island accident, and the far worse 1986 Chernobyl catastrophe, helped stop the industry in its tracks. Public confidence plunged; regulatory pressures, political opposition, and costs surged. And by the 1990s, fossil fuels were cheap enough that nuclear power—even with more-efficient designs—wasn't worth pursuing. Instead, U.S. utilities dotted the landscape with advanced natural-gas-fired power plants.

But today, natural-gas prices are three times what they were 10 years ago, making all alternatives, from wind turbines to nuclear reactors, more attractive. Abroad, 24 nuclear plants—including eight in India, four in Russia, and three in Japan—are now under construction. And in the United States, several utilities are reconsidering the nuclear option. Why not simply build new plants, which would benefit from three decades' worth of technology advances in materials, sensors, and control software? Today's 104 operating U.S. nuclear power plants, after all, reflect the designs of the 1960s and the technologies of the 1970s. But the job of actually building plants requires much more than better technology; it requires partnerships, public relations, and lobbying to overcome the ghosts of the recent past.

Entergy Nuclear of Jackson, MS, already operates 10 nuclear power plants over eight locations, and it would like to build more at some of those sites. But as a practical matter, the company realized it needed to band together with others in the industry to reduce its exposure to market risk, promote enough competition between major reactor suppliers to yield an affordable design, sell the communities near the sites on the plants' economic benefits, and extract federal subsidies. Entergy also believed it needed to try to replace the "No Nukes" slogan of yesterday with a "No CO_2" slogan for today. In essence it's pushing the idea that the slight risk of meltdown and the proliferation of bomb ingredients are lesser evils than global warming triggered by the buildup of carbon dioxide from fossil fuels *(see "Environmental Heresies," May 2005)*.



If Entergy builds a new nuclear power plant, the company might locate it at its existing site in Port Gibson, MS.

PAUL NEHRENZ / ENTERGY CORPORATION

Entergy Nuclear

FY 2004 revenues: $1.3 billion
Employees: 6,052
Number of nuclear power plants: 10

Entergy knew it needed to tread carefully, especially at the outset. "If one utility was to step out [and propose a nuclear plant], they could become the lightning rod for the antinuclear community, and for people's concerns on Wall Street," says Dan R. Keuter, Entergy Nuclear's vice president for nuclear-business development. As the last U.S. nuclear plants were being built in the 1970s and '80s, delays caused by new regulatory pressures, political opposition, construction problems, and the slow issuance of operating permits caused enormous cost overruns.

So in 2003, Entergy, along with the Chicago-based utility Exelon, took the lead in forging a coalition. The companies called five other utilities and suppliers to a meeting near the Atlanta airport. "We called it the 'Atlanta seven' meeting, and our goal was to see if we could respond together to come up with a new reactor design and share those costs and those risks," Keuter recalls. Out of that meeting came a consortium called NuStart, which now includes nine power companies and two major reactor builders, Westinghouse and GE. Each member contributes $1 million annually to the consortium's joint operations.

The consortium has revived the approach to nuclear power that prevailed in the 1950s, says Andrew Kadak, a nuclear engineer at MIT. One of the first nuclear power plants, Yankee Rowe in Rowe, MA—completed in 1960—was built by 10 utilities who shared costs and the resulting power. NuStart "is an important new initiative for the industry," says Kadak. "The new initiative may end up being the same model [as the one of the 1950s]." But before construction of a plant can begin, the utilities will need two permits from the U.S. Nuclear Regulatory Commission. The first would approve the site selection, the other the construction and operation of the reactor.

The design question is fairly simple. While some farther-out technologies, such as the helium-cooled pebble bed modular reactor—an updated version of the gas-cooled reactors prototyped over the past 30 years in Germany and the United States—are being pursued in China and South Africa, NuStart is betting on so-called evolutionary advances in the tried-and-true water-cooled designs that predominate today. In this basic design, water flows through a superhot reactor core, creating steam to drive turbines.

The goal of the evolved design is to keep things as simple and affordable as possible without compromising safety. Today's U.S. nuclear plants include at least two redundant sets of safety equipment, including auxiliary pumps to supply cooling water to the reactors and auxiliary diesel generators to keep the equipment humming. One way of reducing the need

for such systems is to make safety systems "passive." For instance, huge tanks of water placed uphill can, in an emergency, flood reactors without the use of power or pumps. "You can make [nuclear power plants] cheaper with less equipment, and that was the reason for the focus on passive safety," says Keuter. Improvements in a range of supporting technologies, he argues, have enabled the construction of very safe plants. "Instrumentation and control systems have become much smaller and faster and solid state and more reliable, all of which allow you to monitor the operation more precisely."

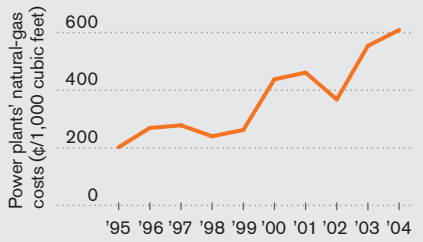
In its drive to execute a new power plant design, the NuStart coalition is benefiting from generous federal subsidies. NuStart and the U.S. government are splitting the $400 million to $500 million cost of coming up with the detailed designs for two versions of evolutionary water-cooled reactors, one from General Electric and the other from Westinghouse. The NRC has already approved a Westinghouse design for a 1,000-megawatt reactor; General Electric is readying the design of a 1,500-megawatt reactor for NRC approval later this year. Both of these reactors incorporate passive safety features.

After settling on a pair of possible designs, the consortium approached the delicate question of where to actually build a new plant. It was helped by a 1992 change in federal law that streamlined the permitting process. Previously, the NRC would authorize the construction of a reactor and then, when it was finished, issue a separate operating permit. The 1992 change created a combined construction and operating license.

In May, the NuStart coalition announced it had settled on six potential sites: Entergy's Grand Gulf Nuclear Station in Port Gibson, MS, and River Bend Nuclear Station in St. Francisville, LA; Constellation Energy's Calvert Cliffs Nuclear Power Plant in Lusby, MD, and Nine Mile Point Nuclear Station in Scriba, NY; and two federally owned sites, the Bellefonte Nuclear Plant in northeast Alabama, owned by the Tennessee Valley Authority, and the Savannah River Site, a U.S. Department of Energy facility near Aiken, SC. Of these, the coalition plans to pick two by October 1; it will then apply for construction and operation permits for both.

Gas Trend Benefits Nuclear

Almost all the power plants built in the past decade burn natural gas. But surging natural-gas prices have made alternatives, including nuclear power, more competitive.



SOURCE: U.S. ENERGY INFORMATION ADMINISTRATION

Now that NuStart has broken the ice, some utilities—members of the consortium and nonmembers alike—have gone ahead with their own permit applications or announcements. Three companies have applied for site permits: Entergy at Grand Gulf; Exelon Generation at a site in Clinton, IL; and Dominion Nuclear—which is not a member of NuStart—at its North Anna plant in Virginia. Finally, though it hasn't applied for a site permit, Duke Energy of Charlotte, NC, says it is planning to seek an NRC combined construction-operation permit for an undisclosed site. Each of these plants would use one or the other of the two competing NuStart designs. The companies also say they need the U.S. Congress to continue subsidizing the process; subsidies are part of the president's proposed energy bill.

Of course, technologies such as wind turbines and hybrid cars also make a good case for government subsidies. The nuclear industry is promoting itself as a pathway to the hydrogen economy. The electricity produced by a nuclear power plant can split water into hydrogen and oxygen through electrolysis, without creating air pollution. And hydrogen can also be produced directly: the extremely high temperatures inside nuclear reactors can be used to split water molecules.

None of the utilities applying for NRC permits has ordered a new reactor. But if one or more actually goes ahead, it could open the door to investments in a new generation of more efficient plants. "If they are successful in getting new plant construction started in the United States during the next three to five years, that will open the door for other nuclear technologies," says Regis Matzie, chief technology officer and senior vice president at Westinghouse, who is also a director of the South African consortium seeking to build a pebble bed plant in that country. "Further, restarting nuclear build in the United States will have a profound impact on new nuclear build around the world."

In a pebble bed reactor, the uranium fuel is encased in billiard ball–sized graphite spheres. The reactor is cooled by helium gas, so it can operate at much higher temperatures than water-cooled plants do, greatly increasing its efficiency. In addition, the technology's advocates argue, pebble bed plants are ideal for hydrogen production because their operating temperatures make it easier to split water into oxygen and hydrogen without electrolysis. "The success of NuStart should be of great value to [the South African consortium] for the future," says Matzie.

But there is an inescapable problem with any nuclear-energy strategy: waste. In the past two decades, the U.S. government has spent some $6 billion to develop an underground storage repository at Yucca Mountain, about 140 kilometers from Las Vegas. But there are serious questions about whether the mountain is dry enough to prevent waste containers from eroding for many thousands of years *(see "A New Vision for Nuclear Waste," December 2004)*. "The industry should be trying to solve the waste problem. If they want more nuclear power plants, there's not going to be enough space at Yucca. They are going to have to keep visiting this issue over and over again. If they don't, it will come back to haunt them," says Allison Macfarlane, a geologist at MIT and editor of a forthcoming book on Yucca Mountain (*Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*).

While the waste problem remains unsolved, current trends favor a nuclear renaissance. Energy needs are growing. Conventional energy sources will eventually dry up. The atmosphere is getting dirtier. But resurrecting the industry will prove to be a delicate task. Neither Entergy nor any other U.S. company has committed to actually building a nuclear power plant. Entergy says that it will wait to see whether Congress approves subsidies before making its next move. **David Talbot**

Apple Switches to Intel Chips

THE DECISION: Apple sees greater risk in staying with IBM's chips than in aligning itself with Intel.

Steve Jobs delights in surprising people. Still, it was a shocker, given the long history of Apple's role as the rebellious alternative to Microsoft's and Intel's dominance of personal computing, when he announced in early June that Apple will henceforth develop its Macintosh computers around chips from Intel. By the end of 2007, all of Apple's personal computers will switch from the PowerPC line of processors to Intel's chips, which have powered the dominant PC architecture since 1981.

The PowerPC has served Apple well. In 1991, Apple announced it would move from Motorola's 68000 processor family to what would become the PowerPC, a chip that it would design in collaboration with IBM and Motorola. The decision to switch was made in part because complex-instruction-set computer (CISC) chips like the 68000 and Intel's x86 chips were thought to have run their course, and because Apple wanted to move to a RISC (reduced-instruction-set computer) architecture, which it thought would give it better performance over the long run. For a time, that seemed to be true, though exact performance comparisons between Macs and PCs are difficult to make.

But claims of superiority have become harder to sustain. In the past 10 years, the difference between CISC chips and RISC chips has blurred: though nominally CISC chips, Intel's most recent Pentiums have many of the design features that gave RISC chips their edge. Worse, the latest generation of the PowerPC used too much power and threw off too much heat to work well in notebook computers, especially the miniaturized notebooks known as subnotebooks, which have very cramped innards. That meant Apple was certain to fall behind in the laptop market, which was faster growing and more profitable than the desktop market. In his remarks on the shift from the PowerPC, Jobs mentioned Apple's frustration at being unable to offer a notebook version of its G5 Macs.

Jobs saw no imminent solution to the power problem. Future production plans from IBM, which, with Freescale Semiconductor (formerly Motorola's processor unit), manufactures the PowerPC, apparently didn't reassure him. In part, that may have been because Apple accounts for just a fraction of PowerPC sales. Because of the power problem, and the uncertainty of IBM's commitment to the chip, "It was very clear that Apple was in a predicament with the PowerPC," says Tim Bajarin, president of Creative Strategies, a consultancy in Campbell, CA. As Jobs said in June, "As we look ahead, we can envision some amazing products we want to build for you, and we don't know how to build them with the future PowerPC road map."

In about two years, all of Apple's Macs will run on Intel chips.

Apple Computer

FY 2004 revenues: $8.3 billion
FY 2005 revenues through Q3: $10.3 billion
IBM and Freescale's current share of the PC processor market: 1.8 percent

Seen one way, Apple's move to Intel is hardly shocking. Apple has over the past several years moved its PC hardware toward standard components, such as the universal serial bus (USB) and the peripheral component interconnect (PCI). Apple's products matter not because they use different hardware but because they are elegant. And though most people attribute much of the Mac's elegance to its operating system, Apple could be moving toward making it possible for a Mac to be loaded not just with Apple's operating system, but with Windows as well; once the Mac is using an Intel chip, it will probably be able to run Windows in native mode. Current Mac users can already run Windows XP using an emulation program.

Apple's decision to move to Intel has its risks. Processor transitions are not simple, in large part because they require software migration. But Apple has proven that that's a problem it can handle. In the early 1990s, it brought its software from the 68000 to the PowerPC, and in 2001, it moved to OS X, a revamped operating system. The biggest risk of the switch to Intel, in fact, has nothing to do with what Apple can *do*, but rather with what it can prevent others from doing. "Every hacker in the world will try to make the Mac OS run on [PCs]," says Roger Kay, an analyst at International Data Corporation. "If it happened, it would tank their business." Still, Kay notes that there are ways to prevent the Mac OS from being hacked. Apple is certain to pursue them.

According to Jobs, the first Macs that use Intel processors won't be available until June 2006, so there's also the risk of the Osborne Effect—the name applied (perhaps unfairly, given the history of 1980s PC maker Osborne) to the phenomenon of a premature new-product announcement hurting sales of existing products. But Apple has more than $2 billion in cash on hand and a cash cow in the iPod: it can probably weather any short-term losses.

In moving to Intel, Apple is betting that it can improve its fortunes by buying chips from a company that is sure to be focused on PCs for the foreseeable future. IBM, for its part, is moving from the business of hardware to the business of services *(see "Research in Development," May 2005)*. It could well be that all the major companies involved—Apple, IBM, and Intel—will be better for the move. **Michael Fitzgerald**

COURTESY OF APPLE COMPUTER

By Invitation Ian H. Hutchinson

Fusion Research: What about the U.S.?

Fusion, though long-term, is a worthy investment.

Ian H. Hutchinson is head of the Department of Nuclear Science and Engineering at MIT. He and his team designed and built a major national fusion research facility, which he directed for its first 10 years of operation.

THE SITE FOR the International Thermonuclear Experimental Reactor (ITER) has finally been chosen: southern France. Both the European Union and Japan were bidding to host ITER, and the selection of one of them opens the way to the scientific demonstration of controlled fusion energy production and removes perhaps the last major impediment to a project under consideration for nearly 20 years.

This result is good news for the two bidders, for the rest of the ITER consortium (the United States, Russia, China, and South Korea), and for the citizens of the world, since it enables us to take the next step toward developing a sustainable energy source—nuclear fusion, the process that powers the sun—that produces zero climate-changing emissions.

Nuclear reactions that release energy by combining light nuclei like hydrogen's to form heavier nuclei such as helium's are called fusion. They are, in a sense, the opposite of the fission reactions that generate power in present-day nuclear plants. Fission breaks up the nuclei of heavy elements such as uranium. Fusion has the potential to provide practically inexhaustible energy with greatly reduced radioactive waste.

ITER will use a donut-shaped magnetic containment device called a tokamak.

But confining a plasma tightly enough to enable useful energy release is far more difficult than early researchers had hoped. Many important optimizations have been developed, but one unavoidable measure is to make the plasma large. Existing large tokamaks typically have a plasma radius of three meters and have demonstrated substantial energy releases. But keeping their fuel in a plasma state has required additional heating.

The next big step is to create a plasma that keeps itself hot with its own fusion reactions. The ITER collaboration has designed a reactor that should sustain such a "burning plasma." It will require a plasma about twice as large as those produced by current tokamaks and superconducting magnets that consume negligible electric power. ITER will cost about $5 billion to construct.

Fusion is the kind of grand technological challenge that calls for international coöperation. But the length of time its development will require can breed skepticism and discourage policymakers. In the mid-1990s, cuts in the United States' fusion research budget led it to pull out from the ITER consortium. Thankfully, it rejoined in 2003, but in a more junior role, reflecting its relatively modest funding of fusion projects: $290 million in 2006, less than half Europe's commitment.

Fusion's grand challenge requires global coöperation—and U.S. research funding.

The fuel in a fusion reaction must be subjected to tremendous heat, which turns it into an electrically conducting gas called a plasma. The plasma state must be maintained long enough for the reactions to occur. In stars like our sun, gravity confines the plasma in a wonderfully stable and long-lived configuration. A human-scale fusion reactor must use a much stronger confining force: a magnetic field.

The United States still has two world-renowned tokamaks—one at MIT, the other at General Atomics in San Diego—whose research will be crucial in helping to resolve and prepare for challenges that ITER faces. But U.S. leadership in fusion plasma science cannot be sustained without a renewed commitment of resources. The United States' present 10 percent share of ITER will call for peak expenditures of perhaps $150 million per year—mostly for industrial procurements, not for research.

If that money were taken from the existing federal fusion research budget, it would decimate U.S. fusion research. That is why the U.S. fusion community's overwhelming enthusiasm for ITER is predicated on strong domestic support for fusion and plasma physics research, plus additional funds for ITER construction. Even if the U.S. increased its funding for fusion research to $500 million per year, that would still be substantially less than it spends separately on high-energy physics, fossil energy research, and basic energy sciences, not to mention the recent budgets of the Missile Defense Agency ($9 billion) and NASA ($16 billion).

Ultimately, fusion could prove to be one of the most environmentally attractive energy options. The United States should seize the opportunity to play a strong role in ITER's success and demonstrate its commitment and long-term vision as a scientific collaborator by revitalizing its overall fusion program. ■

STEPHANE MANEL

U.S. stem cell researchers confront uncertain financing and arcane restrictions.

Can the science survive under these conditions?

ON AUGUST 9, 2001, MATHEW "WILLY" LENSCH SAT WITH his wife in their Oregon living room and watched President George W. Bush speak to the nation. Millions of Americans had their TVs on, but unlike most of them, Lensch was, as he puts it, "on the edge of my chair, the rest of the universe ceasing to exist."

Lensch was finishing his PhD in molecular and medical genetics. His research specialty was a genetic malady called Fanconi anemia, which often kills its victims before they reach adolescence. The disease is caused by the malfunctioning of special cells in the bone marrow: stem cells, the precursor cells that create and maintain the body's supply of blood cells. Fanconi victims' best hope for a cure, Lensch believed, lay in re-creating their missing blood cells from *embryonic* stem cells—stem cells derived from an early human embryo, which are unusually adaptable and changeable. Earlier that year, Lensch had accepted a position with a brand-new stem cell group that is now based at Children's Hospital Boston, a prominent biomedical research center.

By Charles C. Mann
Photographs by Dana Smith

That evening, the president was addressing the nation about embryonic-stem-cell research—which was why Lensch was glued to the TV, watching "with fear and trepidation." Extracting stem cells from an embryo unavoidably destroys it, and in 1996 the U.S. Congress prohibited the government from supporting embryo-destroying research. But despite this measure, scientists had found legal ways to obtain embryonic stem cells, and now some of the president's supporters were urging him to outlaw embryonic-stem-cell research entirely. Lensch had switched on the television to find out whether what he believed was his chance to help cure an awful disease was going to vanish (along with his new job).

To his relief, Bush tried to find a middle ground. Arguing that scientists had already created "more than 60 genetically diverse stem cell lines," the president decided to "allow federal funds to be used for research on these existing stem cell lines, where the

Willy Lensch's first reaction to Bush's stem cell policy was relief. Today, that strikes him as naïve.

life-and-death decision has already been made." But Uncle Sam would not spend any money on *new* stem cell lines. With this compromise, Bush argued, researchers would be able "to explore the promise and potential of stem cell research without crossing a fundamental moral line."

At first, Lensch was relieved, even elated. The administration had crafted regulations that allowed publicly funded research on existing embryonic stem cells and hadn't called for the banning of privately funded research on new cell lines. "I really thought we might be up and running in a few months," Lensch says.

Today, that reaction strikes him as naïve. Bush's apparently simple decision to withhold federal money inadvertently created an enormous regulatory maze that few scientists have managed to escape. Four years after the president's speech, Lensch's team has not yet been able to begin a full research program. Its story is not unusual: with a few exceptions, private funding sources—philanthropies and businesses—have not stepped into the gap left by Washington's withdrawal. Nor have research groups been able to capitalize on federal funding for the study of existing stem cell lines, partly because they are fewer in number than Bush thought, and partly because of unexpected patent restrictions.

Worse, Lensch says, the small amount of stem cell research that has been permitted is taking place almost entirely without the benefit of public scrutiny. "When research is tied to the federal government, there's a whole structure of oversight to make sure that it's performed for the public good," he says. "When you cut the tie, it's the Wild West—there's no rules.... In the name of preserving morality, the president's decision has ended up creating moral anarchy."

Early Start

In November 1998, James Thomson, a developmental biologist at the University of Wisconsin–Madison, announced that he had isolated human embryonic stem cells. (A few days later, John D. Gearhart of the Johns Hopkins University School of Medicine made a similar claim.) The quiet, publicity-shy Thomson eventually found himself on the cover of *Time*. Little wonder: embryonic stem cells, many researchers believe, will change medicine as dramatically as did antibiotics. But the thousands of press accounts rarely mentioned *where* Thomson isolated his stem cells, or why he did it there—something that, at least in the short run, may prove almost as important.

To biologists, embryonic stem cells are fascinating entities. After birth, almost every cell in the human body is committed to fulfilling a single function: a red blood cell is always and forever a red blood cell; a neuron is always and forever a neuron. Even bone marrow stem cells can transform themselves into only a few types of blood cells. Embryonic stem cells are different. They form in the first few days after sperm meets egg; about 30 of them cluster on the interior wall of the blastocyst—a hollow ball of about 150 cells that develops around the time the embryo reaches the uterus from the fallopian tube. These 30 cells—from which researchers derive embryonic-stem-cell lines—are identical, but as the embryo grows they differentiate into the more than 200 types of cells that make up the human body. Not only are harvested embryonic stem cells a powerful new tool for studying disease, scientists believe, but they may lead to a new era of regenerative medicine, in which sick people effectively replace their damaged parts. In theory, doctors should be able to stimulate them when needed to grow replacement tissues and organs—producing new hearts and livers in a petri dish, so to speak.

Thomson obtained his stem cells from embryos created at in-vitro fertilization (IVF) clinics in Wisconsin and Israel. Because IVF frequently fails, doctors use drugs to induce female patients to "superovulate," producing as many as 15 eggs at once. These are placed into a bath of sperm, creating multiple fertilized eggs. Each egg is allowed to divide, usually into an embryo of six to eight cells. Doctors then insert several embryos through a catheter into the woman's uterus and hope that one attaches successfully. The rest are usually frozen in liquid nitrogen. Since 1978, the year the first successful IVF baby was born, U.S. clinics alone have built up a surplus of more than 400,000 frozen embryos, according to a 2003 study by Rand, a nonprofit think tank in Santa Monica, CA. Clinics preserve more than 90 percent of these frozen embryos in case couples want to try for additional pregnancies. About 2.8 percent are donated to research.

After receiving his six- to eight-cell embryos, Thomson grew them to blastocyst stage and then extracted their stem cells, destroying them in the process. He destroyed *many* embryos, in fact, because most frozen embryos either don't survive thawing or can't produce cell lines that will survive for long. Thomson needed 36 embryos to establish his five cell lines. Other researchers have required even more. Researchers at Eastern Virginia Medical School in Norfolk, VA, used more than 100 IVF embryos to create three embryonic-stem-cell lines in 2001.

Because of the U.S. Congress's 1996 prohibition on using federal money for "research in which a human embryo or embryos are destroyed," Thomson could not work in his own laboratory, which was supported by the National Institutes of Health and the National Science Foundation. Instead he created a second workplace from scratch, a couple of windowless rooms at the edge of campus, three kilometers from his main lab—"fairly primitive conditions," as he puts it, "with only the bare necessities." Unable to use his own technicians (their salaries were covered in part by federal grants), Thomson did most of the bench work himself, rising before dawn for days on end and going to bed late at night. He funded the research with money from the Wisconsin Alumni Research Foundation (WARF), an independent nonprofit that has sponsored UW-Madison research since 1925, and Geron, a biotech startup in Menlo Park, CA. (Geron also backed Gearhart's research and that of a stem cell group at the University of California, San Francisco.)

Lensch was sure that Bush's cell lines would not be enough. To begin with, many of them were probably abnormal.

As per Thomson's agreement with his university, he awarded WARF the basic patents on embryonic stem cells. After a legal dustup, Geron won the exclusive commercial rights to three ma-

George Daley is struggling to continue his promising research and still comply with fickle federal restrictions.

jor potential stem-cell uses. Despite controlling the sole supply of the hottest discovery in cell biology since DNA, WARF was not bombarded by requests for the right to work with Thomson's stem cell lines. "Scientists questioned whether or not they should risk their career on a field that had so much political and financial controversy around it," says Andrew Cohn, government and public-relations manager at WARF.

Geron could not fund an entire field of research single-handedly, says David Greenwood, the company's chief financial officer. Nor could it get access to capital through the route of partnering with pharmaceutical companies. Even though it is widely believed that stem cells will ultimately become the center of a huge new medical industry, Geron president Thomas Okarma has said, drug companies so fear today's controversies that they remain "completely uninterested." Most venture capital firms are leery, too. "The administration says it is letting us go ahead, within certain broad guidelines," says Greenwood. "Meanwhile, there is legislation dropped into every session of Congress that would literally criminalize what we do." (The current version of the legislation would impose a prison term of "not more than 10 years" on anyone who inserted genetic material into embryo cells, which many researchers would like to do to study the development of particular genetic conditions.)

Even Thomson could not make much headway. "If you do a quick PubMed search on my name," he says in an e-mail, "you will see from 1998–2001 we published almost nothing. We had little or no access to standard equipment because of the prohibition on the use of federal funds that was in effect at that time, and it severely limited what we could do."

Then came Bush's announcement, which Cohn says led "a lot of people" to decide "that they could now go ahead."

One of them was Willy Lensch.

Patent Problems

From the beginning, Lensch was sure that Bush's cell lines would not be enough. To begin with, many of them were probably abnormal. The genetic information in eggs and sperm is so often fraught with random errors and mismatches that the resulting embryos are frequently not viable. Embryos from IVF clinics are no exception, so researchers cannot assume that the stem cell lines derived from them are genetically normal.

But even when lines are normal, they degrade over time. Creating enough stem cells for a single lab's experiments—let alone for distribution to other labs—requires coaxing the cells to divide over and over. Across many generations, the cells accumulate random genetic mistakes. In consequence, Lensch says, "you always need new supplies of cell lines. There's no escaping it."

At the time Lensch came to Massachusetts, the National Institutes of Health was compiling a list of stem cell lines created before the president's speech, all of which were approved for federally funded research. Wanting to work with as many as possible, Lensch and his coworkers contacted stem cell researchers everywhere from San Francisco to Stockholm to Melbourne, asking to borrow samples in the sort of free exchange that has long characterized scientific research.

To Lensch's dismay, he says, "there were lots of closed doors, lots of *no*s, lots of no-answers." Driven by greed (the huge potential commercial impact of embryonic stem cells) and fear (the huge potential for liability), laboratories around the world refused to share data and expertise. A colleague forwarded to Lensch an e-mail from a Swedish scientist who flatly explained

that his group was not letting other Swedes work with its stem cell lines, or even conducting experiments with them itself at the time. An Australian group was willing to make its stem cells available, Lensch says, "but it was during the foot-and-mouth outbreak there." To export the cells to the U.S., the Australians "had to provide documentation that they were free of agriculturally important infections. And of course nobody in Australia had tested the lines for foot-and-mouth disease," he says. Six months after joining his new lab, Lensch had only a single line, from Thomson's collaborator, Joseph Itskovitz-Eldor of the Technion-Israel Institute of Technology, in Haifa.

All the while, he was negotiating for two lines with the University of California, San Francisco (UCSF), another Geron-funded lab. In the past, Lensch says, a researcher who borrowed materials developed by a second researcher usually came back after making an interesting discovery to offer coauthorship of the resulting paper, thus spreading around the glory. As universities have become more intent on exploiting their intellectual property financially, they have begun asking borrowers to sign formal "materials transfer agreements" that spell out what can be done with borrowed materials. Usually the agreements authorize specific researchers to work with the materials, describe what the materials can be used for, and list the circumstances under which the materials' creators must be given credit in publications. The UCSF agreement, in Lensch's view, went further. "To begin with, they could stop your research at any time," he says. "And whatever I could make with [the two stem cell lines], they would continue to own. In effect, I became an employee of UCSF."

Lensch eventually obtained both cell lines from UCSF in September 2002. But Harvard University, which is affiliated with Children's Hospital Boston, is still negotiating licensing terms with WARF, whose stem cell patents cover a wide range of applications. According to Patrick Taylor, chief counsel for research affairs at Children's Hospital, WARF is protecting its intellectual property with an "unfortunate perseverance" that, in a kind of negative synergy, has coupled with the Bush regulations to impede stem cell research.

WARF's Cohn denies that the foundation has created hurdles. "Our goal is to distribute the cells as quickly and painlessly as possible for both researchers and us," he says, noting that some 250 research teams now use WARF lines. "We don't make money doing this. In fact, we lose money doing this—$1.3 million so far. It's part of our commitment to moving the science forward."

But because WARF holds patents so fundamental to stem cell research, Taylor says, it effectively controls much of the field. WARF obtained such rights, Taylor argues, only because the "federal abdication of funding" meant that it had anomalously few rivals. And while the government demands that the researchers it backs minimally restrict their colleagues, most private organizations don't. So privatizing every aspect of this fundamental new research will lead to "a thicket of conflicting patents" that will make it "extremely difficult to do any research."

Exemplifying Taylor's worries are the hundreds of patents, patent filings, and exclusive licenses with which Geron has further locked up prime intellectual property. The company might provoke less complaint if it were a pharmaceutical giant like Merck or Pfizer that can support researchers around the world. But Geron has spent only $90 million on stem cell research since 1995. As Geron's Greenwood admits, the company can support only a handful of labs, which have free access to its intellectual property. Everyone else is out in the cold.

The result, in Taylor's view, is a classic instance of the law of unintended consequences: because the federal government won't support most stem cell research, the work must be sponsored by private industry. But no corporation will support research that it can't benefit from. The same regulations that open the door for private industry also effectively shut it.

Daley's Dilemma

Children's Hospital is near a Boston neighborhood historically full of doctors that is referred to, predictably, as Pill Hill. Children's has almost a dozen buildings on its main campus and more than 4,000 doctors, nurses, and staff members overall. One of its buildings houses the world's biggest pediatric research lab.

In an upper-floor wing of another, smaller building is Lensch's new stem cell lab. To the casual visitor, it looks much like any other biomedical research center. There are long lines of lab benches punctuated by computer screens and white and gray machines. Shelves are crammed with bottles and jars bearing cryptic, hand-scrawled labels. The only slight oddity is that several small rooms in this otherwise tightly packed space are empty of everything but a few boxes and pieces of what looks like discarded equipment. In these unused spaces, Children's Hospital hopes to experiment with embryonic stem cells.

The separate rooms are a consequence, in part, of George Daley's conclusion that pushing stem cell research forward would require shifting from federally supported "presidential" cell lines to "nonpresidential" lines—ones that had not been isolated before Bush's 2001 speech. Daley, who directs Lensch's research, first arrived at Children's in November 2003, lured by its offer of a brand-new facility and some startup money. (Until then, he had worked at MIT's Whitehead Institute for Biomedical Research.) A prominent blood researcher, Daley wanted to unlock the mechanisms of bone marrow diseases like leukemia and aplastic anemia. He quickly saw the potential of embryonic stem cells and won one of the first NIH grants to study them.

As Daley discovered when planning the stem cell facility, "going nonpresidential" meant that he had to ensure that it was *not* supported by federal money. The rules created endless bureaucratic tangles and drove up costs enormously. Says Erik Halvorsen of Harvard's Office of Technology Development, which handles licensing on the stem cell lines developed by Harvard researcher Douglas Melton, at first "nobody understood what it meant when you couldn't use federal funds. Did that mean [the government couldn't pay for] anything in the lab space? Did that include things down to the level of the individual pipette? What if federally approved and nonfederally approved research were in two adjoining rooms? Did that mean the government could pay up to a certain percentage for things like heating?"

To be "on the safe side," he says, Harvard created a completely separate facility with brand-new equipment for Melton's team. Children's took another route, sequestering its stem cell work in special, isolated rooms—setting up a second laboratory,

more or less, inside the first. The tools used by a research group—such as electron microscopes, DNA synthesizers, and centrifuges—can together cost up to a million dollars per scientist. Laboratories typically reduce those costs by sharing equipment among research teams. But as a practical matter, that won't work for stem cell research, because most scientific equipment at major research institutions is at least partly funded by the federal government. Inadvertently, Daley says, the president's decision made embryonic-stem-cell research much more expensive.

But equipment and facilities weren't the only added costs. To ensure that it was complying with federal guidelines, Taylor says, "Children's gathered together the senior management from each of the affected areas—finance, intellectual property, sponsored research, compliance, clinical research, research ethics, and administration, together with legal and accounting staff." The managers conducted Talmudic studies of the 106 sections of the U.S. Office of Management and Budget's Circular A-21 that establish the "cost accounting standards" for distinguishing unallowable "facilities and administration costs," which for Children's included the heating and janitorial expenses for the stem cell rooms. In the process, Daley says, they ended up "creating an entire parallel oversight system, which sounds easy but, if you've ever tried it, is time consuming and expensive."

As an example, Daley cites the internal registration sheet, common to almost all research facilities, which scientists periodically fill out "to let their institutions know who is doing what." According to Daley, the lab administrators charged with designing the relevant form for the Children's stem cell program wanted it to ask scientists to certify that their experiments "were being reviewed by Finance to ensure they were privately funded, had institutional review-board clearance, had clinical-studies application, had obtained their lines through a proper materials transfer agreement, and so on."

At the top of the form, researchers are asked to describe the purposes of their research. "We've had an enormous back-and-forth about how much information to provide," Daley says. Scientists want maximum flexibility to take advantage of serendipitous discoveries on the lab bench, whereas lawyers want the thickest paper trail possible. With animal experiments, Daley says, standards have been worked out. "Since nobody has worked in embryonic stem cells, we've had to set that balance all over again. That's okay, but now we have no guidance from the federal government. Everybody's off on their own, wondering if they are doing the right thing." Designing the registration sheet, he says, consumed hundreds of hours of time.

Despite all the effort invested in untangling the federal restrictions, Lensch says, some questions are still unanswered. "If you have a stem cell line, it's alive," Lensch says. "If you break the cells open and extract their RNA, that's not alive. But it's a derivative [of the live cell lines], so you still can't work with it. Now, the *data* you generate from that RNA—can *they* be included in an NIH-approved experiment?" If researchers experiment on nonpresidential embryonic stem cells "in a building floating in space over international waters and publish the results, is it complicit for a federally funded researcher to read it? Can an editor or publisher at a federally funded institution publish it? Believe me, we have been wondering that." Nobody in the group, he says, "wants to end up making license plates."

Even as regulations upped costs, they shrank the financing pool. Not only has the ban on federal funding closed the coffers of NIH and NSF and created inhospitable conditions for industry, but it has also scared off much private philanthropy. Among those saying no to embryonic-stem-cell research are the American Heart Association and the American Cancer Society.

Among those saying no to embryonic-stem-cell research are the American Heart Association and the American Cancer Society.

With many funding sources shut off, researchers must seek support from wealthy individuals and smaller groups, such as the Juvenile Diabetes Research Foundation. In the future, researchers in stem-cell-friendly places like California, Massachusetts, and Wisconsin may be able to draw on special earmarked funds created by state legislatures, though state funding is already raising a new set of legal and logistical questions.

Researchers can cobble together funding from these and other sources, but many at Children's still bemoan the federal government's lack of involvement. NIH usually awards long-term, relatively open grants. Unsurprisingly, smaller outfits tend to be more narrowly focused; they typically give short-term grants with specific benchmarks. But in brand-new fields like stem cells, researchers are bound to need more latitude.

More important, Daley says, the federal government sets the rules in the research world. For decades, NIH and NSF have gradually established a set of procedures that all institutions must follow if they are to receive federal research funding. The rules range from the need to obtain informed consent from research subjects to requirements for transparency in record-keeping. When the government suddenly absents itself, Daley says, nobody knows whether the rules still apply and whether they will be enforced.

"If things get worse, the best scientists may simply drop out," Taylor says. "That would be a tragedy. Who will be left then—the people who want to make headlines cloning babies?"

Made in Korea

"We'll get through this," Daley says. "But it's terribly frustrating having to move at a crawl when the science is so exciting—and when other nations are flying ahead." In May, Daley learned with a pang that Korean scientists had discovered how to create patient-specific embryonic stem cells—exactly the kind of breakthrough work that he and Lensch want to do in trying to understand genetic blood diseases. "No disrespect to them," Lensch says, "but I couldn't help thinking that we could have done that." He sighs. "I really do think that we could've done that if we'd had the chance." ■

Charles C. Mann's just published book is 1491: New Revelations of the Americas before Columbus. *His website can be found at www.charlesmann.org.*

R&D 2005

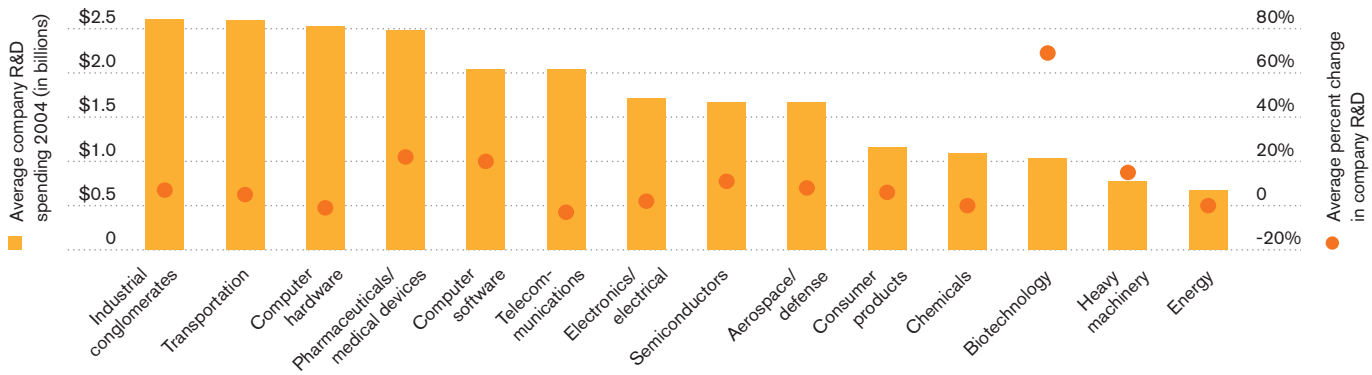
Technology Review's annual look at corporate research trends shows that pharmaceutical and biotech companies are outpacing those in other tech sectors in their R&D investments.

THE 2005 EDITION OF THE *TR* R&D SCORECARD SHOWS that worldwide corporate spending is picking up, but that the gains are unevenly distributed. The biggest advances are in the life sciences, which also happen to be among the most research-intensive industries: 2004 R&D spending among the biotech companies on the list shot up by an average of 69 percent over the previous year. The gain at pharmaceutical companies was less spectacular but still a strong 22 percent. IT companies, on the other hand, have as a group barely increased their R&D outlays; telecommunications and computer hardware companies, on average, spent *less* than in 2003. Spending in telecom remains particularly troubled, with several leading companies, including Motorola, Ericsson, and NTT, reporting double-digit decreases. In IT, however, software remains an exception; Microsoft paced the sector to a 20 percent increase in research spending in 2004. The scorecard ranks companies by the *Technology Review* Innovation Index, which takes into account R&D spending levels, spending increases, and R&D as a proportion of sales; five of the top 10 companies according to this metric are in life sciences.

But numbers alone don't tell the corporate research story. Another indicator of vibrant R&D is willingness to invest in visionary projects that may not pay off for many years—if ever. In this spirit, we spotlight three "blue sky" research efforts *(p. 52)*. Intel's use of lasers to detect biological molecules with exquisite sensitivity could help researchers understand the causes of cancer and other diseases. Lucent Technologies' Bell Labs—which has in the past decade severely curtailed the basic research that once made it such a jewel—is making progress toward the radical concept of quantum computing. And IBM has launched an effort to use supercomputers to model the human brain. These projects provide a heartening counterweight to the common charge that industry is overly fixated on next quarter's results.

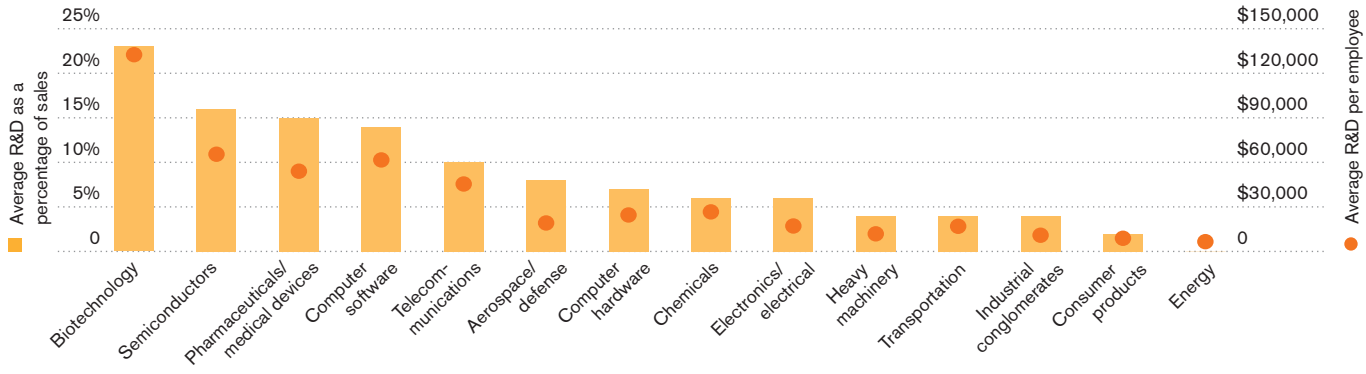
Where the Growth Is

Research budgets at biotechnology, pharmaceutical, and computer software companies grew the most last year.



Big Spenders

Four industries—biotech, semiconductors, pharmaceuticals/medical devices, and software—spent significantly more on R&D, proportionally, than the others.



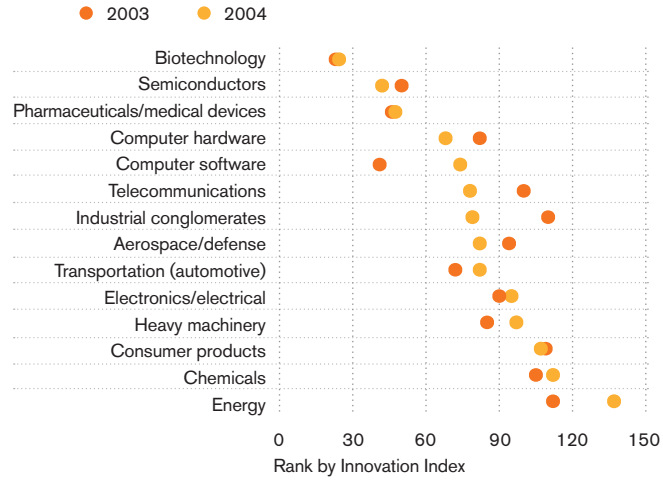
TR Innovation Index—The Top 15

The Innovation Index is calculated by combining, with equal weights, 2004 R&D spending rank, percent change in R&D spending, absolute change in R&D spending, and R&D spending as a percentage of sales.

Rank by Innovation Index	Company name	R&D spending 2004 (in millions)	R&D percent change	Absolute change in R&D (in millions)	R&D as a percentage of sales
1	SANOFI-AVENTIS*	$9,483	466%	$7,809	50%
2	MICROSOFT	$7,779	67%	$3,120	21%
3	BIOGEN IDEC*	$688	195%	$454	31%
4	GENERAL MOTORS	$6,500	14%	$800	3%
5	MERCK (U.S.)	$3,885	22%	$707	17%
6	PFIZER	$6,613	-7%	-$518	13%
7	JOHNSON & JOHNSON	$5,203	11%	$519	11%
8	INTEL	$4,778	10%	$418	14%
9	DAIMLERCHRYSLER	$7,197	2%	$111	4%
10	GLAXOSMITHKLINE	$5,275	2%	$89	14%
11	FORD MOTOR	$7,400	-1%	-$100	4%
12	NOVARTIS	$4,207	12%	$451	15%
13	ASTRAZENECA	$3,803	10%	$352	18%
14	ROCHE	$4,210	7%	$269	16%
15	SIEMENS	$6,441	0%	-$5	7%

Innovative Sectors

The overall Innovation Index rankings of six industries, including semiconductors, computer hardware, and telecommunications, improved in 2004.



*SANOFI-AVENTIS AND BIOGEN IDEC ARE BOTH IN THE TOP THREE BECAUSE OF DUPLICATED R&D EXPENSES FOLLOWING RECENT MERGERS. NEXT YEAR, AFTER THE DUST SETTLES, THESE COMPANIES MAY NO LONGER RANK SO HIGH.

IBM

The Computer Brain

BY DAVID TALBOT The neocortex constitutes the bulk of the human brain and is the presumed seat of learning, language, memory, and whatever it means to be human. It contains many billions of neurons, and each neuron can interact with nearby neurons in thousands of different ways. The operations of even a single neuron are difficult to measure, and biologists don't agree on how many distinct subclasses of neurons are present in the neocortex, how the six layers of the neocortex interact with one another, and whether the system behaves differently from one part of the neocortex to the next. "It's a humongous mess," says Michael Beierlein, a neuroscientist at Harvard Medical School. And when neuroscientists study the electrochemical processes that take place in that mess, "ultimately we just don't know what the crucial features are, and which ones we can safely ignore: what is biological noise, what is important, what is an experimental artifact."

Neuroscientists around the world are trying to decipher the neocortex, because understanding it better could provide insights into everything from psychiatric disorders and brain disease to learning and memory. To that end, many groups are trying to create computer models of how neurons function. A research project launched this year by IBM is the most ambitious such effort ever attempted: the company and Swiss research partners hope to create a functioning 3-D model of a two-millimeter chunk of neocortex containing 60,000 neurons—a unit known as a neocortical column. The neuron modeling project "is going to be larger than anything done before, by an order of magnitude," says Charles Peck, the computer scientist at IBM's T. J. Watson Research Center in Yorktown Heights, NY, who heads the project, dubbed "Blue Brain."

The researchers will take raw data collected from rat neurons at the Swiss Federal Institute of Technology in Lausanne and feed it into an IBM supercomputer that is among the world's fastest. Henry Markram, the Swiss neuroscientist heading the biological end of the project, says a graphical representation of just the 10,000 neurons in a rat neocortical column will require up to two terabytes of storage—roughly the amount of data that can be held in 400 standard recordable DVDs. IBM computer scientists experienced in simulating biological systems will help build a 3-D model that mimics the interactions of these neurons and compare its performance against Markram's laboratory data.

The ambitious "Blue Brain" supercomputer project aims to create a 3-D computer model of the enormously complex way that neurons function in the human brain.

The job will be vast. "Think of a neuron as a tree, with roots and branches," says Markram. "Imagine if you take 60,000 of these trees and squeeze them in the space of a pinhead. That is the kind of architecture you are looking at, with the roots of trees touching branches of other trees." And that's just for one neocortical column; the human neocortex is estimated to contain tens of millions of them. But if all goes well, "we will be able to see where the information goes, how it is represented, and how it is stored on a tree," Markram says. "Then we can understand what can go wrong." Markram believes the project could yield possible targets for drugs to treat brain diseases in 10 years.

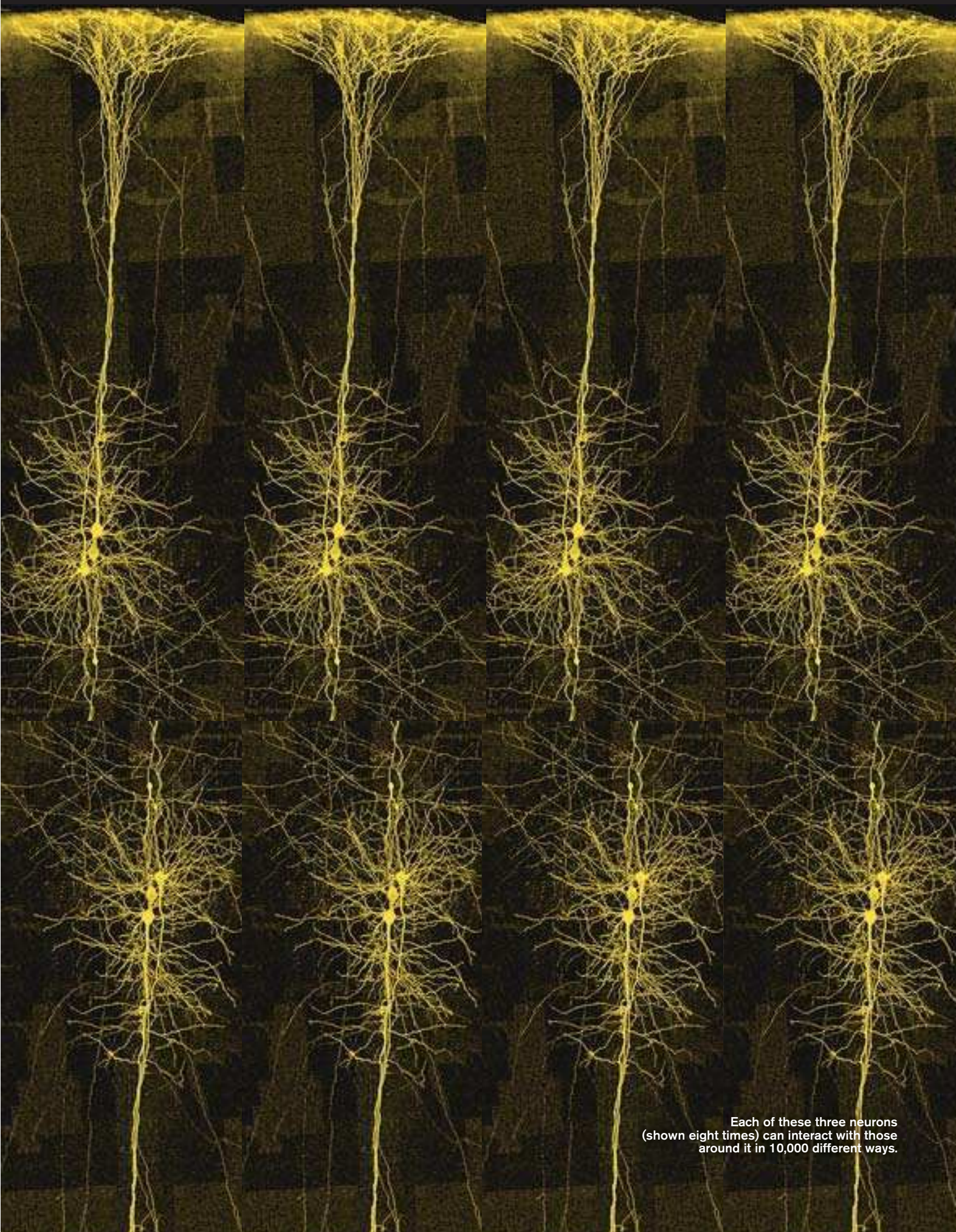
That is certainly ambitious. "The simulation may lead to a better understanding of some of the circuitry," says Tai Sing Lee, a computer scientist and neurophysicist at the Center for the Neural Basis of Cognition, a joint project of the University of Pittsburgh and Carnegie Mellon University. However, he adds, "Simulating the human brain and curing disease are extremely far away." Viewed against the magnitude of the task, says Lee, IBM's Blue Brain project is worthwhile but "a small step in biology."

Intel

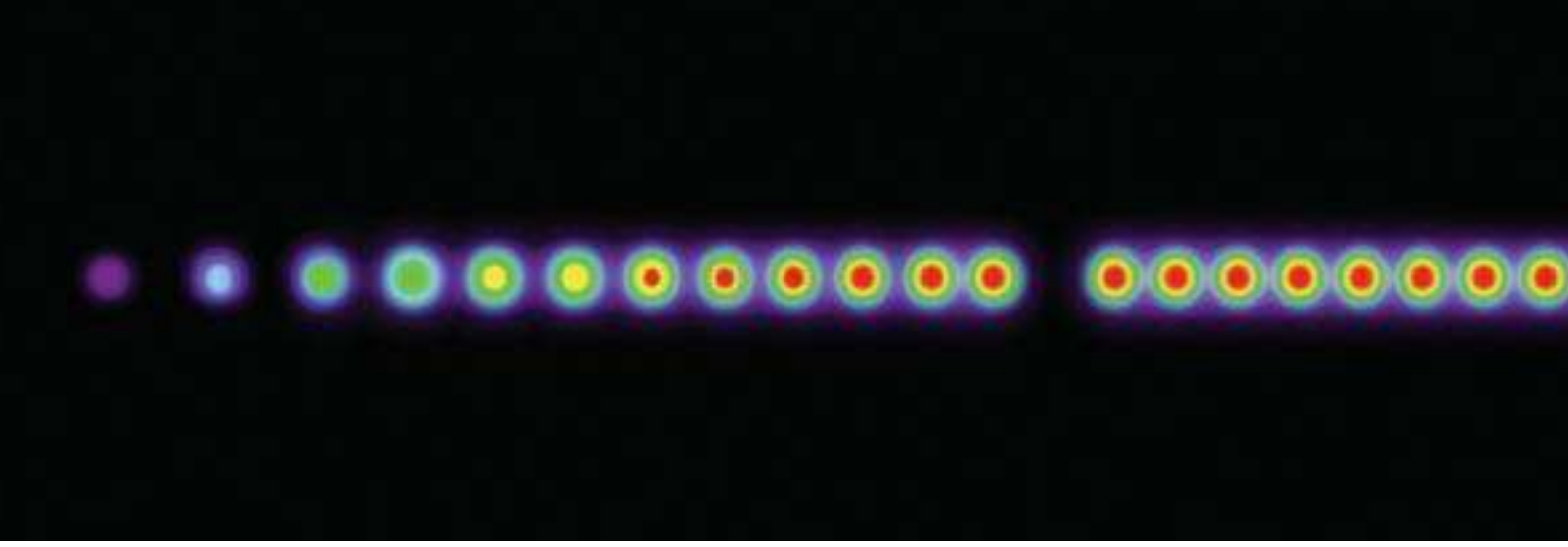
Precision Biology

BY CLAIRE TRISTRAM Ever since James Watson and Francis Crick unveiled their helical model of DNA in 1953, it has been an iconographic symbol of science. But no matter how familiar the structure of DNA becomes, observing the molecular pieces from which it is built remains a tantalizing challenge—and one for which a number of competing technologies are being developed. A tool that consistently offers researchers a way to observe biological processes at the molecular level would be invaluable. In particular, the ability to closely observe the nucleotides that make up DNA, combined with the ongoing work on the human genome, could even-

COURTESY OF IBM/EPFL BLUE BRAIN PROJECT



Each of these three neurons (shown eight times) can interact with those around it in 10,000 different ways.



tually yield more-powerful methods for diagnosing disease.

At Intel, technologists pursuing better biological imaging have adopted an analytical method widely used in semiconductor R&D. In May, Intel's Precision Biology group published a paper describing its use of Raman spectroscopy to detect single molecules of two of the four nucleotides that make up DNA: deoxyguanosine monophosphate (dGMP) and deoxyadenosine monophosphate (dAMP). While single molecules of dAMP had previously been detected with Raman spectroscopy, dGMP molecules had not. And Intel's approach greatly improved the consistency with which a Raman effect was detected. "We wanted to push the limits of sensitivity," says Andrew Berlin, lead researcher for the five-year-old group.

By scattering laser light off a biological sample, researchers can detect DNA components with single-molecule precision—an advance that could lead to new ways to diagnose disease.

Raman spectroscopy takes advantage of the fact that light beams passing through different substances will scatter in different ways, emerging with different sets of characteristic wavelengths. Such patterns can serve as fingerprints for identifying specific compounds. The Raman approach offers advantages over other technologies for single-molecule detection, in that it's one of the most sensitive techniques available and can also be used to detect molecules in a very dilute solution of water—or potentially in the watery world of a cell. What's more, the technique provides a way to directly observe molecules without labeling them with fluorescent tags.

One way to intensify the Raman effect is to induce it in close proximity to metal. Berlin's team, adapting techniques already being used by Intel in its manufacturing processes, first created a layer of silicon that was pocked with nanoscale pores to increase the area of the surface to which molecules could bind. They next coated the silicon with molecules containing silver and deposited a biological sample on the coated surface. The group bombarded the sample with pulses from multiple lasers and, in recent experiments, caused a single nucleotide to emit a signal strong enough to be detected. "We're right in the middle of one of the best labs in the world for optimizing nanoparts, so we could take advantage of all the experience that comes out of our processor research," Berlin says.

The significance of Intel's approach is that it can boost a molecule's signal so dramatically—between 100 and 10,000 times, depending on the molecule being studied—that it will allow observation of single molecules without chemically altering them. "The Intel experiments are the first that demonstrate the great potential of this kind of Raman technique for detecting single molecules," says Eric O. Potma, who is working on similar research at the University of California, Irvine. Also, while fluorescent labeling is used only for taggable molecules, Intel's research will likely find broader applications. "With single-molecule Raman, we might be able to monitor the details of molecules that have remained invisible to us with fluorescence spectroscopy," says Potma.

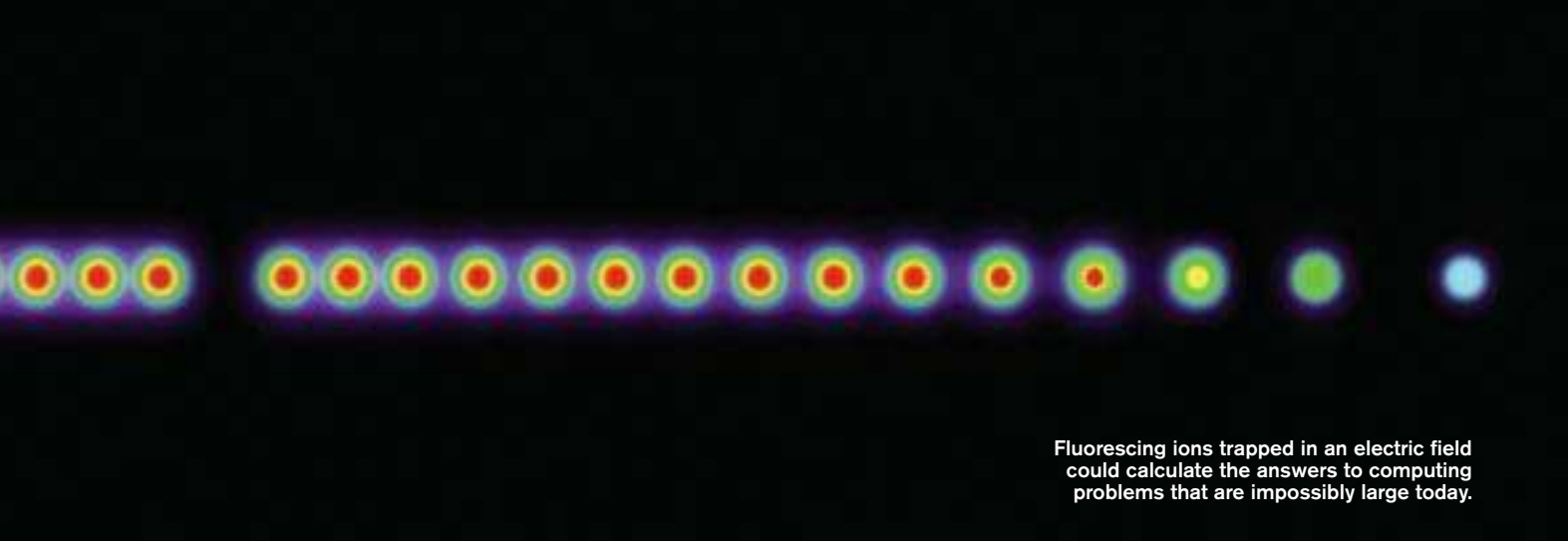
The ability to better see how molecules operate could help fulfill a dream cherished by many biologists. "Being able to study single molecules will transform our thinking," says cell biologist Mark Roth of the Fred Hutchinson Cancer Research Center in Seattle, which is collaborating with Intel on this project.

Bell Labs

Quantum Computing

BY DAN CHO More than half a century after inventing the transistor—the foundation for modern electronics, computing, and telecommunications—Lucent Technologies' Bell Labs is pursuing another technology that could radically change information technology: quantum computing. Today's transistors continue to get smaller, allowing computer speeds to double every one or two years. But a quantum computer would leap way

JOHN MACNEIL



Fluorescing ions trapped in an electric field could calculate the answers to computing problems that are impossibly large today.

A computer that manipulated quantum qubits could solve certain problems millions of times faster than today's machines.

ahead of that pace. If such a machine is finally built, it will offer the ability to solve certain problems millions of times faster.

A conventional computer stores information as bits, which are represented as *1*s and *0*s. Quantum computers rely on quantum bits, or qubits, which can hold values of *1*, *0*, or—and this is the part that defies intuition—some quantum blend of those two values. Another quantum effect known as "entanglement" allows two or more qubits to coördinate their behavior, even when they don't appear to be interacting.

These strange properties would make qubits extremely powerful tools for attacking certain computing problems, such as factoring large prime numbers in encryption applications and searching huge databases. (Two Bell Labs researchers, Peter Shor and Lov Grover, devised breakthrough quantum algorithms for solving these two problems in the 1990s.)

But creating the hardware that can harness qubits presents a huge challenge. Qubits are encoded as the spins of individual particles like atoms, ions, or photons. These particles must be isolated so that they can't interact with their surrounding environment, which would ruin the quantum computation. Bell Labs researchers, like several other groups, are pursuing a method for controlling qubits with a device called an ion trap. Each trap is between a tenth and a hundredth of a millimeter long and has tiny electrodes that can hold an ion in place above it in an electric field, while a laser beam alters the ion's spin. When the computation is complete, the ion is excited by a different laser, causing it to give off photons that can be recorded by a camera to reveal its final state, which represents part of the answer to a problem.

Research groups working with trapped ions have so far produced quantum computations using fewer than 10 qubits. To be of any practical use, though, a quantum computer will require hundreds or thousands of qubits. The qubits might be held in an array of many traps, known as a multiplex system, with connections for shuttling ions back and forth between different regions to prepare them for a computation, read their final states, and even store them in memory. While most ion traps are currently made of ceramic, Bell Labs is working to design a multiplex system in silicon. Transistors could supply voltage from an external source wherever it's needed, eventually allowing researchers to position thousands of ion traps on a single chip, says Richart Slusher, head of Bell Labs' quantum computing team. Bell Labs expects to fabricate some of these multiplex traps in the next two years, says Slusher.

The Bell Labs group has "thought about the long-range problem, including how you do all the electronic controls," says David Wineland, head of the Ion Storage group at the National Institute of Standards and Technology, a leading center of quantum computing research. According to Wineland, the ceramic traps that scientists have been using in current experiments have "obvious limits." But what will ultimately replace them, he says, "is still open for question."

Building ion traps on silicon would allow researchers to take advantage of the semiconductor industry's decades of working knowledge. David Bishop, Bell Labs' vice president for physical-sciences research, thus believes that all the basic technologies for quantum computing are ready—or that they soon will be. "We don't see any fundamental show stoppers," says Bishop.

Still, most researchers in the field, including Wineland and Slusher, do not expect a practical quantum computer to appear for at least another decade. Even then, the first machines will be built to solve very specific computing tasks. And while solving just, say, the factoring problem would have profound implications in cryptography, a quantum computer may not be any better than a conventional machine for many of the tasks that a desktop PC routinely handles.

None of this dissuades Bell Labs—which has eliminated much of its fundamental R&D in recent years—from pursuing what is, really, still a basic research project. Part of its motivation is the belief that the hardware research may pay off for Lucent long before quantum computers arrive, yielding advances in areas such as miniaturized lasers and optical components. "What we learn from working in the quantum computing field may someday lead to commercialization," says Bishop, "but more importantly, it also drives discoveries that could improve today's communications and computing technology." ■

Technology Review ranks the top 150 spenders across a broad range of technology-intensive industries.

Corporate R&D Scorecard

Company name (country)	Rank by Innovation Index	R&D spending 2004* (in millions)	R&D percent change	Absolute change in R&D (in millions)	R&D as a percentage of sales	R&D per employee	Research focus
Aerospace/defense							
BAE SYSTEMS (U.K.)	21	$3,196	–	$13	19%	$43,598	Aircraft, ships, submarines, communications, electronics, guided weapons
FINMECCANICA (Italy)	35	$1,879	–	–	20%	$36,822	Aircraft, aircraft components, technology systems, combat vehicles
EADS (Netherlands)	65	$2,704	-3%	-$80	7%	$24,439	Materials, engineering, electronics, sensors, information technology
BOEING (U.S.)	80	$1,879	14%	$228	4%	$11,818	Aircraft, electronics, airport technology, engineering, energy systems
UNITED TECHNOLOGIES (U.S.)	92	$1,256	22%	$229	3%	$5,990	Energy systems, environmental control, engineering, engines
HONEYWELL INTERNATIONAL (U.S.)	103	$917	22%	$166	4%	$8,413	Security, sensors, environmental control
LOCKHEED MARTIN (U.S.)	121	$962	7%	$59	3%	$7,400	Aircraft, ships, electronics, energy systems, engineering
ROLLS-ROYCE (U.K.)	137	$524	–	$2	5%	$14,885	Aerospace, ships, energy systems
Average	**82**	**$1,665**	**8%**	**$77**	**8%**	**$19,170**	
Biotechnology							
BIOGEN IDEC (U.S.)	3	$688	195%	$454	31%	$161,196	Oncology, immunology, congestive heart failure
AMGEN (U.S.)	22	$2,028	23%	$373	19%	$140,833	Cancer biology, inflammation, metabolic disorders, neurology, hematology
SERONO (Switzerland)	27	$595	27%	$127	24%	$121,339	Reproductive health, neurology, dermatology, growth and metabolism
GENENTECH (U.S.)	42	$816	30%	$189	18%	$106,706	Oncology, immunology, vascular biology
Average	**24**	**$1,032**	**69%**	**$286**	**23%**	**$132,519**	
Chemicals							
BAYER (Germany)	73	$2,680	-13%	-$391	7%	$23,719	Health care, crop protection, materials, information technology
BASF (Germany)	101	$1,492	6%	$87	3%	$18,204	Biotechnology, genetic engineering, chemistry, nanotechnology
MONSANTO (U.S.)	102	$511	–	$1	9%	$40,556	Crop protection, genomics, crop genetics, chemicals
DUPONT (U.S.)	106	$1,333	-1%	-$16	5%	$22,217	Materials, chemicals, biology
AKZO NOBEL (Netherlands)	109	$1,047	-7%	-$81	6%	$17,037	Pharmaceuticals, coatings, chemicals
SUMITOMO CHEMICAL (Japan)	111	$703	3%	$22	6%	$36,939	Nanoscale materials, fuel cells, genomics, proteomics, chemistry
DOW CHEMICAL (U.S.)	124	$1,022	4%	$41	3%	$23,656	Chemicals, plastics, crop science, energy
MITSUBISHI CHEMICAL (Japan)	126	$828	-3%	-$24	5%	$24,711	Petrochemicals, performance products, functional materials, health care
SOLVAY (Belgium)	130	$525	2%	$11	5%	$17,931	Pharmaceuticals, chemicals, plastics
SYNGENTA (Switzerland)	142	$809	11%	$82	11%	$41,411	Crop protection, genomics, crop genetics, chemicals
Average	**112**	**$1,095**	**0**	**-$27**	**6%**	**$26,638**	

*BASED ON DATA FOR MOST RECENT FISCAL YEAR, ENDING MAY 31, 2005. SOURCES: STANDARD AND POOR'S; COMPANY WEBSITES; *TECHNOLOGY REVIEW*

Company name (country)	Rank by Innovation Index	R&D spending 2004* (in millions)	R&D percent change	Absolute change over 2003 (in millions)	R&D as a percentage of sales	R&D per employee	Research focus
Computer hardware							
IBM (U.S.)	23	$5,167	2%	$99	5%	$15,705	Deep computing, displays, e-commerce, semiconductors, storage
SUN MICROSYSTEMS (U.S.)	38	$1,926	5%	$89	17%	$59,080	Business PDA applications, device networks, speech technology, Java
TOSHIBA (Japan)	55	$3,149	2%	$49	6%	$19,523	Film, optics, wireless communication, transistors
HEWLETT-PACKARD (U.S.)	59	$3,506	-4%	-$146	4%	$23,219	Internet systems, wireless communication, security, privacy, printing
EMC (U.S.)	72	$848	18%	$129	10%	$37,352	Storage
FUJITSU (Japan)	90	$2,346	-12%	-$326	5%	$15,025	Internet services, ubiquitous computing, computational science, security
NEC (Japan)	91	$2,400	-13%	-$370	5%	$16,739	Banking systems, e-government systems, optical, IP and device networks
SEIKO EPSON (Japan)	114	$833	-2%	-$13	6%	$9,808	Printers, projection, electronic components, optics
Average	**68**	**$2,522**	**-1%**	**-$61**	**7%**	**$24,556**	
Computer software							
MICROSOFT (U.S.)	2	$7,779	67%	$3,120	21%	$136,474	Multimedia, search, knowledge management, security, machine learning
ELECTRONIC ARTS (U.S.)	41	$633	24%	$122	20%	$103,398	Enterprise software, extensible systems, open-source software
SAP (Germany)	62	$1,298	3%	$33	14%	$40,290	Business process applications, e-business
AUTOMATIC DATA PROCESSING (U.S.)	96	$581	16%	$82	7%	$13,837	Data processing and outsourced services
ORACLE (U.S.)	118	$1,278	8%	$98	1%	$30,678	Grid computing, Web services, Java, Linux, open-source software
COMPUTER ASSOCIATES (U.S.)	122	$690	4%	$28	20%	$45,098	Mobile gaming, motion capture, 3-D face and body rendering
Average	**74**	**$2,043**	**20%**	**$581**	**14%**	**$61,629**	
Consumer products							
ALTRIA GROUP (U.S.)	74	$809	6%	$47	1%	$5,186	Food safety, nutrition, obesity, health and wellness products
PROCTER AND GAMBLE (U.S.)	86	$1,802	8%	$137	4%	$16,382	Fats and oils, absorbent structures and materials, perfumes
NESTLÉ (Switzerland)	110	$1,168	17%	$172	2%	$4,728	Packaging materials, infant nutrition, clinical nutrition
UNILEVER GROUP (Netherlands)	133	$1,355	-9%	-$128	2%	$5,645	Nutrition, culinary products, hair care, deodorants, household products
L'ORÉAL (France)	134	$645	6%	$34	3%	$12,383	Polymers, niosomes, hair color, céramides, sunscreens, emulsifiers
Average	**107**	**$1,156**	**6%**	**$52**	**2%**	**$8,865**	
Electronics/electrical							
MATSUSHITA ELECTRIC (Japan)	17	$5,756	6%	$339	7%	$17,195	Display technology, multimedia, electronic products
SONY (Japan)	28	$4,695	-2%	-$117	7%	$28,979	Semiconductors, robotics, nanomaterials, fuel cells, networking, devices
PHILIPS ELECTRONICS (Netherlands)	45	$3,223	-3%	-$106	8%	$19,949	Display technology, lenses, device networks, semiconductors, batteries
CANON (Japan)	54	$2,574	6%	$151	8%	$23,781	Cameras, sensors, optics, nanomaterials
HITACHI (Japan)	57	$3,477	-1%	-$50	4%	$11,331	Nanoelectronics, home networks, bioinformatics, mobile communications,
AGILENT TECHNOLOGIES (U.S.)	82	$917	-13%	-$134	13%	$32,750	Communications, molecular biology, nanoscale science, photonics
FUJI PHOTO FILM (Japan)	89	$1,571	-3%	-$50	7%	$21,475	Digital imaging systems, recording/storage media, film and imaging
SHARP (Japan)	95	$1,298	3%	$43	6%	$28,114	Liquid-crystal displays, 3-D-imaging displays, optoelectronics
SANYO ELECTRIC (Japan)	98	$1,233	5%	$62	5%	$12,838	Solar cells, display devices, photonics, robotics, home networks, 3-D
EASTMAN KODAK (U.S.)	99	$839	12%	$89	6%	$15,310	Imaging, sensors, wireless networks, photographic media
AREVA (France)	105	$511	41%	$149	4%	$7,298	Energy, nuclear power, electrical, electronic and optical connectors
RICOH (Japan)	107	$865	11%	$84	5%	$11,829	Cameras, printers
SCHNEIDER ELECTRIC (France)	115	$681	8%	$52	5%	$8,022	Electrical distribution, automation, and control
LG ELECTRONICS (Korea)	120	$1,144	–	–	3%	$36,195	Consumer electronics
MATSUSHITA ELECTRIC WORKS (Japan)	128	$538	9%	$43	4%	$10,737	Materials, software, optical switches, lighting
SUMITOMO ELECTRIC (Japan)	131	$517	14%	$62	4%	$5,913	Information technology, communications, electronics, automotive systems
XEROX (U.S.)	141	$760	-12%	-$108	5%	$13,081	Microelectromechanical systems, optoelectronics, integrated systems
MITSUBISHI ELECTRIC (Japan)	144	$1,276	-24%	-$402	4%	$12,895	Internet computing, advanced graphics, digital TV, multimedia
ALSTOM (France)	150	$602	-24%	-$190	3%	$7,833	Information and communication technologies, power electronic systems
Average	**95**	**$1,709**	**2%**	**-$4**	**6%**	**$17,133**	
Energy							
TOTAL (France)	116	$808	NA	NA	1%	$7,251	Oil exploration, petroleum refining, renewable energy
EXXON MOBIL (U.S.)	146	$649	5%	$31	–	$7,555	3-D seismic technology, drilling, energy
ROYAL DUTCH/SHELL (Netherlands)	149	$553	-5%	-$31	–	$4,938	Chemicals, energy
Average	**137**	**$670**	**0**	**0**	**0**	**$6,581**	

Company name (country)	Rank by Innovation Index	R&D spending 2004* (in millions)	R&D percent change	Absolute change in R&D (in millions)	R&D as a percentage of sales	R&D per employee	Research focus
Heavy machinery							
ABB (Switzerland)	48	$690	13%	$77	3%	$6,729	Nanotechnology, microelectromechanical systems, software, wireless
ITT (U.S.)	88	$634	13%	$75	9%	$14,409	Electronic interconnects and switches, defense communications
CATERPILLAR (U.S.)	93	$928	39%	$259	3%	$12,064	Fuel cells, machines, engines, power generation
VOLVO (Sweden)	117	$1,011	6%	$56	3%	$12,928	Transportation, telematics, Internet applications, databases, ergonomics
JOHN DEERE (U.S.)	139	$612	6%	$34	3%	$13,153	Engines, agricultural equipment
Average	**97**	**$775**	**15%**	**$100**	**4%**	**$11,857**	
Industrial conglomerates							
SIEMENS (Germany)	15	$6,441	–	-$5	7%	$14,978	Materials, light, imaging, robotics, user interfaces, logistics
GENERAL ELECTRIC (U.S.)	70	$2,443	16%	$340	2%	$7,958	Ceramics, energy, environmental electronics, imaging, photonics
ISTITUTO FINANZIARIO INDUS. (Italy)	85	$2,222	–	–	3%	$11,542	Automotive and transport (Fiat and Comau), engine technology, materials
3M (U.S.)	100	$1,143	4%	$41	6%	$17,042	Light management, film solutions, fuel cells, lighting products
TYCO INTERNATIONAL (Bermuda)	125	$784	17%	$113	2%	$3,034	Fire and building products, flow control, valves, optics
Average	**79**	**$2,607**	**7%**	**$98**	**4%**	**$10,911**	
Pharmaceuticals/medical devices							
SANOFI-AVENTIS (France)	1	$9,483	466%	$7,809	50%	$98,335	Cardiovascular, central nervous system, oncology, internal medicine
MERCK (U.S.)	5	$3,885	22%	$707	17%	$62,056	13 therapeutic areas including arthritis, asthma, cancer, cardiovascular
PFIZER (U.S.)	6	$6,613	-7%	-$518	13%	$57,504	18 therapeutic areas including oncology, cardiovascular
JOHNSON AND JOHNSON (U.S.)	7	$5,203	11%	$519	11%	$47,343	9 therapeutic areas including central nervous system, gastrointestinal
GLAXOSMITHKLINE (U.K.)	10	$5,275	2%	$89	14%	$52,834	Cardiovascular, infectious diseases, gastrointestinal, oncology, respiratory
NOVARTIS (Switzerland)	12	$4,207	12%	$451	15%	$51,688	10 therapeutic areas including metabolic disorders, ophthalmics
ASTRAZENECA (U.K.)	13	$3,803	10%	$352	18%	$59,237	Cardiovascular, gastrointestinal, infection, neuroscience, oncology
ROCHE (Switzerland)	14	$4,210	7%	$269	16%	$65,061	12 therapeutic areas including anemia, virology, infectious diseases
ELI LILLY (U.S.)	20	$2,691	15%	$341	19%	$60,474	Diabetes, genitourinary disorders, central nervous system
WYETH (U.S.)	26	$2,461	18%	$367	14%	$47,871	Women's health, cardiovascular, musculoskeletal, gastrointestinal
AVENTIS (France)	29	$3,720	-15%	-$631	16%	$49,222	Diabetes, asthma, multiple sclerosis
SCHERING-PLOUGH (U.S.)	32	$1,607	9%	$138	19%	$52,689	Infectious diseases, respiratory, arthritis, oncology, cardiovascular
BRISTOL-MYERS SQUIBB (U.S.)	37	$2,500	10%	$221	13%	$58,140	Alzheimer's, oncology, diabetes, hepatitis, HIV/AIDS, obesity
SCHERING (Germany)	44	$1,169	-1%	-$6	19%	$44,738	Gynecology and andrology, diagnostics and radiopharmaceuticals
TAKEDA CHEMICAL (Japan)	61	$1,323	9%	$110	13%	$90,652	Cardiovascular, obesity, diabetes, metabolic disorders
EISAI (Japan)	63	$732	13%	$87	15%	$95,124	Immunology, endocrinology, gastroenterology, neurology, cardiology
DAIICHI PHARMACEUTICAL (Japan)	64	$548	-3%	-$20	18%	$74,271	Infectious diseases, cancer, cardiovascular, rheumatology, ophthalmology
NOVO NORDISK (Denmark)	66	$744	4%	$27	15%	$36,685	Diabetes, hemophilia
ALTANA (Germany)	67	$566	8%	$42	15%	$52,503	Gastrointestinal disorders, respiratory disorders
SANKYO (Japan)	68	$809	–	-$2	15%	$70,259	Cardiovascular
ABBOTT LABORATORIES (U.S.)	75	$1,697	-2%	-$37	9%	$27,999	Infectious diseases, cardiovascular, oncology
BOSTON SCIENTIFIC (U.S.)	78	$569	26%	$117	10%	$32,514	Devices: electrophysiology, peripheral interventions, pulmonary endoscopy
GUIDANT (U.S.)	79	$516	–	-$2	14%	$43,000	Imaging and diagnostics, vascular, bioabsorbable materials
MEDTRONIC (U.S.)	81	$951	12%	$100	9%	$30,786	Cardiac-rhythm management, neurology, cardiac surgery, vascular
MERCK (Germany)	83	$762	-1%	-$7	11%	$26,387	Women's health, respiratory diseases, cardiovascular
ASTELLAS PHARMA (Japan)	94	$550	-16%	-$105	13%	$60,722	Infectious diseases, diabetes, gastrointestinal, central nervous system
BAXTER INTERNATIONAL (U.S.)	138	$517	-7%	-$36	5%	$10,771	Stem cells, biomaterials
Average	**47**	**$2,486**	**22%**	**$385**	**15%**	**$54,032**	
Semiconductors							
INTEL (U.S.)	8	$4,778	10%	$418	14%	$56,212	Microprocessors, silicon, manufacturing, photonics, networking
SAMSUNG ELECTRONICS (Korea)	16	$4,438	36%	$1,168	6%	$71,696	Semiconductors, telecommunications, printers
STMICROELECTRONICS (Netherlands)	30	$1,532	24%	$294	17%	$30,949	Solar cells, nanotechnology, microelectronics, semiconductors
TEXAS INSTRUMENTS (U.S.)	36	$1,978	15%	$253	16%	$55,762	Mobile-device semiconductors
INFINEON TECHNOLOGIES (Germany)	40	$1,551	12%	$165	17%	$43,595	Nanotechnology, photonics, high-frequency circuits, electronic biosensors

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Company name (country)	Rank by Innovation Index	R&D spending 2004* (in millions)	R&D percent change	Absolute change in R&D (in millions)	R&D as a percentage of sales	R&D per employee	Research focus
ADVANCED MICRO DEVICES (U.S.)	43	$935	10%	$82	19%	$58,778	Microprocessors, flash memory devices, low-power processors
ANALOG DEVICES (U.S.)	46	$512	14%	$62	19%	$57,498	Digital-signal-processing technology
BROADCOM (U.S.)	49	$554	-15%	-$100	23%	$202,890	Semiconductors for broadband communications and networking
MICRON TECHNOLOGY (U.S.)	51	$755	15%	$99	17%	$42,173	Semiconductors, image sensors
NEC ELECTRONICS (Japan)	58	$1,009	8%	$79	15%	$41,285	Semiconductors, integrated devices, power management devices
FREESCALE SEMICONDUCTOR (U.S.)	60	$965	-4%	-$40	17%	$43,468	Semiconductors, platforms, process technology
APPLIED MATERIALS (U.S.)	69	$992	8%	$71	12%	$81,361	Semiconductor-wafer fabrication equipment
Average	**42**	**$1,666**	**11%**	**$213**	**16%**	**$65,472**	
Telecommunications							
NOKIA (Finland)	19	$4,749	-1%	-$34	13%	$85,554	4G wireless networks, CDMA, messaging, radio, Semantic Web
CISCO SYSTEMS (U.S.)	25	$3,192	2%	$57	14%	$93,882	Ubiquitous networking based on optical communication technology
NORTEL NETWORKS (Canada)	33	$1,912	-3%	-$62	20%	$55,986	Home networking, optical communications, storage networking
QUALCOMM (U.S.)	47	$720	38%	$197	15%	$94,737	4G network infrastructure, access equipment and terminals, application enablers
ALCATEL (France)	50	$2,019	–	-$8	13%	$36,232	Broadband, imaging, multimedia, microminiaturization, portable energy
ERICSSON (Sweden)	53	$2,916	-23%	-$877	16%	$57,697	Mobile communications, fixed networks, optical networks
LUCENT TECHNOLOGIES (U.S.)	71	$1,270	-15%	-$218	14%	$39,937	Photonics, DWDM, optical Ethernet, IP VPNs, 3G wireless networks
NTT (Japan)	76	$3,318	-10%	-$384	3%	$16,165	Optical networks, wireless networks, network applications, nanotechnology
MOTOROLA (U.S.)	87	$2,797	-26%	-$974	9%	$41,132	Electromagnetic compatibility, high-temperature superconductors
NTT DOCOMO (Japan)	129	$1,164	-1%	-$16	2%	$54,818	Optical networks, broadband
FRANCE TELECOM (France)	135	$717	18%	$109	1%	$3,474	CDMA, digital wireless communications products and services
DEUTSCHE TELEKOM (Germany)	136	$1,145	–	–	2%	$4,680	Speech and sound technologies, multimedia, knowledge processing
BT GROUP (U.K.)	148	$621	-12%	-$85	2%	$6,212	Wireless and satellite broadband, next-generation broadband
Average	**78**	**$2,042**	**-3%**	**-$177**	**10%**	**$45,424**	
Transportation (automotive)							
GENERAL MOTORS (U.S.)	4	$6,500	14%	$800	3%	$20,062	Fuel cells, low-emissions vehicles, sensors, control systems
DAIMLERCHRYSLER (Germany)	9	$7,197	2%	$111	4%	$18,708	Fuel cells, energy, traffic safety, CO_2 reduction, night-vision systems
FORD MOTOR (U.S.)	11	$7,400	-1%	-$100	4%	$22,779	Fuel cells, hydrogen engines, electronics, materials, emissions control
TOYOTA MOTOR (Japan)	18	$6,380	2%	$100	4%	$24,130	Electromechanics, environmental engineering
VOLKSWAGEN (Germany)	24	$4,830	8%	$345	4%	$14,081	Fuel cells, hybrid engines, diesel engines
HONDA MOTOR (Japan)	31	$4,374	4%	$176	5%	$33,239	Hybrid engines, low-emission engines, intelligent community vehicle
BOSCH (Germany)	34	$3,686	9%	$315	7%	$15,212	Diesel engines, micromechanical sensors, multimedia, energy management
NISSAN MOTOR (Japan)	39	$3,723	12%	$410	5%	$31,196	Ultralow-emissions vehicles, active headrests, curtain air bags, fuel cells
BMW (Germany)	52	$2,969	9%	$239	5%	$28,017	Diesel engines, transmissions, lightweight chassis, smart air bags
DENSO (Japan)	56	$2,228	11%	$218	9%	$23,338	Semiconductors, telecommunications, controller logics, energy
FIAT (Italy)	77	$2,302	4%	$80	4%	$14,341	Telematics, multimedia, chassis, climate control, engines
RENAULT (France)	84	$1,759	11%	$178	3%	$13,441	Hybrid engines, diesel engines
PEUGEOT CITROËN (France)	97	$2,366	-11%	-$303	3%	$11,419	Urban drive control, multiplexing, electronic stability program, fuel cells
AISIN SEIKI (Japan)	104	$833	11%	$84	6%	$17,494	Electric vehicles, intelligent transport systems, optical engineering
FAURECIA (France)	108	$746	10%	$69	5%	$11,936	Pedestrian detection, pollution control, materials
VALEO (France)	112	$743	4%	$25	6%	$11,039	Environmentally friendly air conditioning, aromatherapy diffusers
SUZUKI MOTOR (Japan)	113	$812	15%	$104	4%	$21,101	Computerized analysis and virtual-reality simulation, energy conservation
VISTEON (U.S.)	119	$896	-1%	-$7	5%	$12,764	Telematics, multimedia, chassis, climate control, engines
CONTINENTAL (Germany)	123	$674	6%	$40	4%	$8,366	EService center, flight crew management systems
MAZDA MOTOR (Japan)	127	$850	3%	$28	3%	$23,844	Fuel cells, hydrogen engines, electric engines, smart air bags
MICHELIN (France)	132	$857	-5%	-$47	4%	$6,777	Tires, suspension systems, electronics systems
BRIDGESTONE (Japan)	140	$682	3%	$18	3%	$5,996	Nanotechnology, materials, lightweight and low-resistance tires
HYUNDAI MOTOR (Korea)	143	$802	–	–	2%	$15,069	Hydrogen-powered vehicles, fuel cells, hybrid engines, multimedia
JOHNSON CONTROLS (U.S.)	145	$515	6%	$31	2%	$4,187	Interiors, batteries, controls
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InPhase Technologies hopes to bring its novel 3-D storage product to market by next year—and revolutionize how you store your data.

Holographic Memory

By Gregory T. Huang
Photograph by Plamen Petkov

ALTHOUGH THE OFFICES OF IBM AND HEWLETT-PACKARD are nearby, Longmont, CO, is decidedly not Silicon Valley chic. But in this Denver suburb, a radical experiment in data storage is under way. At the headquarters of InPhase Technologies, where the conference rooms are named after ski resorts, chief executive Nelson Diaz holds up a clear plastic disc, about the size of a DVD but thicker, and pops it into a disc drive. A laptop connected to the drive downloads streaming video of an old episode of *Seinfeld* as the drive writes it to the disc.

But this is no ordinary recording process. The disc has more than 60 times the storage capacity of a standard DVD, while the drive writes about 10 times faster than a conventional DVD burner. That means the disc can store up to 128 hours of video content—almost twice enough for the full nine seasons of *Seinfeld*—and records it all in less than three hours.

It's likely to be one of the first commercial systems to use "holographic storage," in which bits are encoded in a light-sensitive material as the three-dimensional interference pattern of lasers. Unlike CDs and DVDs, which store data bit by bit on their surfaces, holographic discs store data a page at a time in three dimensions, enabling huge leaps in capacity and access speed. And InPhase, a 70-person startup spun out of Lucent Technologies' Bell Labs in Murray Hill, NJ, is leading a handful of companies racing to commercialize this optical storage breakthrough.

Three-dimensional memory could dramatically change how we use microelectronics. Many of the remarkable advances in

consumer electronics over the last few years—and much of the economic health of the industry—are directly traceable to the explosion in storage capacity. Web e-mail services routinely offer each of their customers a gigabyte of memory for free. Apple's newest iPod is only possible because of small, cheap hard drives that can hold a staggering 60 gigabytes of data—a storage capacity that just five years ago would have been a lot for a desktop PC. Likewise, cell phones now come with flash memory chips easily able to store address books, calendars, photos, and the like. Meanwhile, CDs and DVDs have already transformed how people listen to music and watch movies. But each of these storage technologies has drawbacks. The density of magnetic materials in hard drives is fast approaching a fundamental physical limit. Flash memory is slow, and a DVD is barely large enough to hold a full-length movie.

Storing data in three dimensions would overcome many of these limitations. Indeed, the theoretical promise of holographic storage has been talked about for 40 years. But advances in smaller and cheaper lasers, digital cameras, projector technologies, and optical recording materials have finally pushed the technology to the verge of the market. And the ability to cram exponentially more bits into infinitesimal spaces could open up a whole new realm of applications.

By storing and reading out millions of bits at a time, a holographic disc could hold a whole library of films. Movies, video games, and location-based services like interactive maps could be put on postage-stamp-size chips and carried around on cell phones. A person's entire medical history, including diagnostic images like x-rays, could fit on an ID card and be quickly transmitted to or retrieved from a database. Eventually, if the hardware becomes affordable for consumers, holographic storage could supplant DVDs and become the dominant medium for games and movies. Portable movie players and phones that download multimedia from the Web would take off. Holographic storage could even compete with the magnetic hard drive as the computer's fundamental storage unit. And on a larger scale, corporate and government data centers could replace their huge, raucous storerooms of server racks and magnetic-tape reels with the quiet hum of holographic disc drives.

InPhase's competitive edge lies in its partnerships with Hitachi Maxell, a leading producer of computer tapes and CD-ROMs, and—as of this May—Bayer MaterialScience, one of the world's largest makers of plastics used in optical discs. These large corporations see holographic techniques as the next step in the evolution of storage. "Our collaboration with InPhase gives us a tremendous opportunity," says Hermann Bach, head of technologies for the Americas at Bayer MaterialScience.

But if and when holographic storage will come to dominate the market is still an open question. InPhase's initial product launch is slated for late 2006, but industry experts, while optimistic, are also cautious. "They have made numerous contributions on the hardware side, in media and materials, and in error correction," says Hans Coufal, manager of science and technology strategy at IBM's Almaden Research Center in San Jose, CA, and an expert on holographic storage. "It's very impressive but still some ways away from a viable product. Not a long ways, but some ways."

Lunchroom Lasers

The idea of holographic storage dates back to the work of Polaroid researcher Pieter J. van Heerden in the early 1960s (and, some contend, to Nobel laureate Dennis Gabor's original theory of holography in 1948). But the technology had never been practical, requiring exceedingly expensive materials and bulky laser setups—unlike the streamlined system from InPhase. Even Bill Wilson, InPhase's chief scientist, was originally skeptical. In 1987, as a fresh PhD in physical chemistry from Stanford University, Wilson joined Bell Labs, turning down a job at IBM, where he would have started working on holographic storage. "I thought the field would be a complete waste of time," he admits.

The turnaround began in the early 1990s, when IBM and other big players started to worry about the limitations of magnetic storage. As storage capacity increases, the magnetic grains that store data on a hard drive get packed closer together. Eventually, each grain's magnetic field will begin to interfere with those of its neighbors, hindering their ability to reliably hold data. Engineers have thought of clever ways to defer this problem, but ultimately, grains in magnetic materials will be too dense to work properly.

Wilson recalls jumping into a friendly argument in the Bell Labs lunchroom about what new technology could eventually take the place of magnetic media—and the relative merits of holographic storage. At the time, the technique was undergoing something of a revival, being investigated by research groups at IBM, Polaroid, Caltech, and Stanford. Wilson and Kevin Curtis, an electrical engineer from Caltech who had recently joined Bell Labs, argued that holographic storage might actually become viable with suitably small and cheap optical components. In discussing the technical issues with their colleagues, they realized the key to making it viable was the material that stored the data.

In holographic storage, a "data beam" holding information is crossed with a "reference beam" to produce an interference pattern that's recorded in a light-sensitive material. To retrieve data from a particular spot, a reference beam is shone onto it, and the combination of the reference beam and the patterned material reconstructs the original data beam, which is read by a digital-camera detector that translates the beam into a series of electrical signals. The recording material is typically either an inorganic crystal or a polymer. Polymers are more sensitive and require less powerful lasers, but they have their own flaws. For instance, when you hit a photosensitive polymer with a laser, it tends to deform, which messes up the data.

In 1994, a materials team at Bell Labs led by chemist Lisa Dhar worked with Wilson and Curtis to produce a "two-chemistry" photosensitive polymer. The researchers mixed one scaffoldlike polymer, which stayed rigid and preserved its structure, with another polymer that reacted to light and stored data. Decoupling the recording material's optical and structural properties let the researchers fine-tune each independently, arriving at a combination of sensitivity and stability that had eluded previous efforts.

Over the next four years, the Bell Labs team got its holographic material to work in conjunction with the latest miniaturized lasers, cameras, and optical components to read and write data. This also required advances in software to correct for errors in storing and retrieving digital bits. In 1998, as a proof of concept, they built a prototype holographic recorder and re-

corded MP3 digital audio in real time. It was a bulky contraption and not particularly efficient. But at that point, says Wilson, "we realized we could build the darn thing."

So in mid-2000, the researchers contacted Nelson Diaz about starting up a company. Diaz had made his name in the storage industry, working as an engineer for nearly 20 years at Digital Equipment Corporation and most recently as a general manager at StorageTek in Louisville, CO, a leading maker of disk and tape drives. When first told of the researchers' focus on holographic storage, he was skeptical: he had heard the hype for years. But the closer he looked at the Bell Labs design, the more he believed. Five months later, he signed on as chief executive of InPhase.

The first order of business, says Diaz, was getting rights to the underlying intellectual property. InPhase negotiated a deal with Bell Labs that gave it ownership of the core patents for the holographic storage system. Then, of course, the company needed funding. In late 2000, before the tech bubble collapsed, InPhase raised $15 million in three weeks "without a business plan," says Diaz. (Storage giant Imation was a first-round investor.) So in December 2000, six researchers from Bell Labs, including Wilson, Curtis, and Dhar, moved out of the suburbs of New Jersey and joined their new CEO in Colorado.

"It will take time and some deep pockets, but we finally have the ability to take this to market," says Demetrios Lignos of InPhase.

Mainstream Media?

Four and a half years later, the company is still working to develop a holographic storage product, explains Demetrios Lignos, InPhase's vice president of engineering. Lignos is another veteran of the storage industry, a bottom-line guy, not one to be impressed by fancy science or research demos. Product development, he says, takes time; in this case, the challenge was shrinking the optical components down while maintaining the insane levels of precision needed to make holographic storage reliable. Now his team of 60 engineers is gearing up for a pilot launch in September 2006 and, if it goes well, a full release to follow. The initial product: a holographic disc drive that reads and writes 300-gigabyte discs.

But don't throw out your hard drive just yet. The cost of InPhase's holographic equipment will be beyond the means of consumers and most digital-content distributors for some time. Sitting in front of six holographic disc drive prototypes, Lignos explains what makes them tick. Inside each breadbox-size drive is an elaborate system of mirrors, lenses, and liquid-crystal displays that manipulates the beam from a single laser. The disc, 130 millimeters in diameter and 3.5 millimeters thick (as compared to 120 millimeters and 1.5 millimeters, respectively, for a DVD), doesn't spin continuously like a DVD but is mounted on a stage that positions it so that the right portion is exposed to the laser beams at the right time. The laser and camera detector are fixed, but the mirrors and lenses move to produce different beam angles. And that's the real trick: unlike a CD or DVD, the disc can store hundreds of pages of data in a single, small area, each one inscribed by the reference beam at a slightly different angle.

The technology is here. The question now is the size of the market. "Will it actually get into the hands of many users? We haven't proven that yet," acknowledges Lignos. For InPhase, the first applications will lie in high-end archiving for data centers, financial institutions, and medical centers. In those markets, holographic storage will compete with magnetic tape, which also has a high storage capacity but is harder to access. It's also less durable, lasting less than 10 years, while holographic discs should last 50 years or more. InPhase also plans to go after high-definition digital video broadcasting and movie distribution for digital theaters: companies such as the Turner Broadcasting System want to archive videos; and one can imagine the next George Lucas extravaganza being delivered to digital cinemas on one disc instead of a stack of 100.

By 2007, InPhase plans to release a consumer electronics product, a chip that could hold up to five gigabytes—enough to store a movie or video game. The chip could compete with flash memory and give handheld devices the ability to quickly download and play back high-resolution content on the fly. InPhase is focusing on video games, where there are fewer global standards than in movie distribution—making it easier for a small company to break in with new technology. And holographic discs have an advantage for content distributors: they are difficult to pirate. Creating a copy requires the same expensive equipment necessary to make the original.

Five to ten years out, holographic storage could become a mainstream consumer technology—or a colossal flop. The still unanswered questions involve the long-term reliability of the components and, of course, cost. The technology must be dependable enough to convince customers to trust it with their most important data yet cheap enough to become ubiquitous.

InPhase will compete with a smattering of other holographic-storage companies. Tokyo-based Optware is targeting consumer video applications with a simpler technology more similar to traditional DVDs. And Aprilis in Maynard, MA, a Polaroid spinoff, is going after some of the same markets that InPhase targets but is also branching out into biometrics applications like fingerprint matching. "I expect them to coexist for a while, until the better one wins," says IBM's Coufal, an industry veteran who adds that the different companies' approaches are all appealing. "Everybody would love it to succeed....Who will win, I don't know."

But whoever wins, holographic storage could change the rules for information technology by opening up the possibilities of working in three dimensions. Until now, storage—indeed, all of microelectronics—has played out mostly on the surfaces of materials. The benefits of exploiting the third dimension could go beyond storage to include more efficient ways to search ultradense databases, like those that store satellite images for mapping and surveillance; new kinds of displays; and even ultrafast processors whose logic circuits are carved into holographic materials.

"It will take time and some deep pockets," says InPhase's Lignos, "but we finally have the ability to take this to market." ■

Gregory T. Huang is Technology Review*'s senior writer.*

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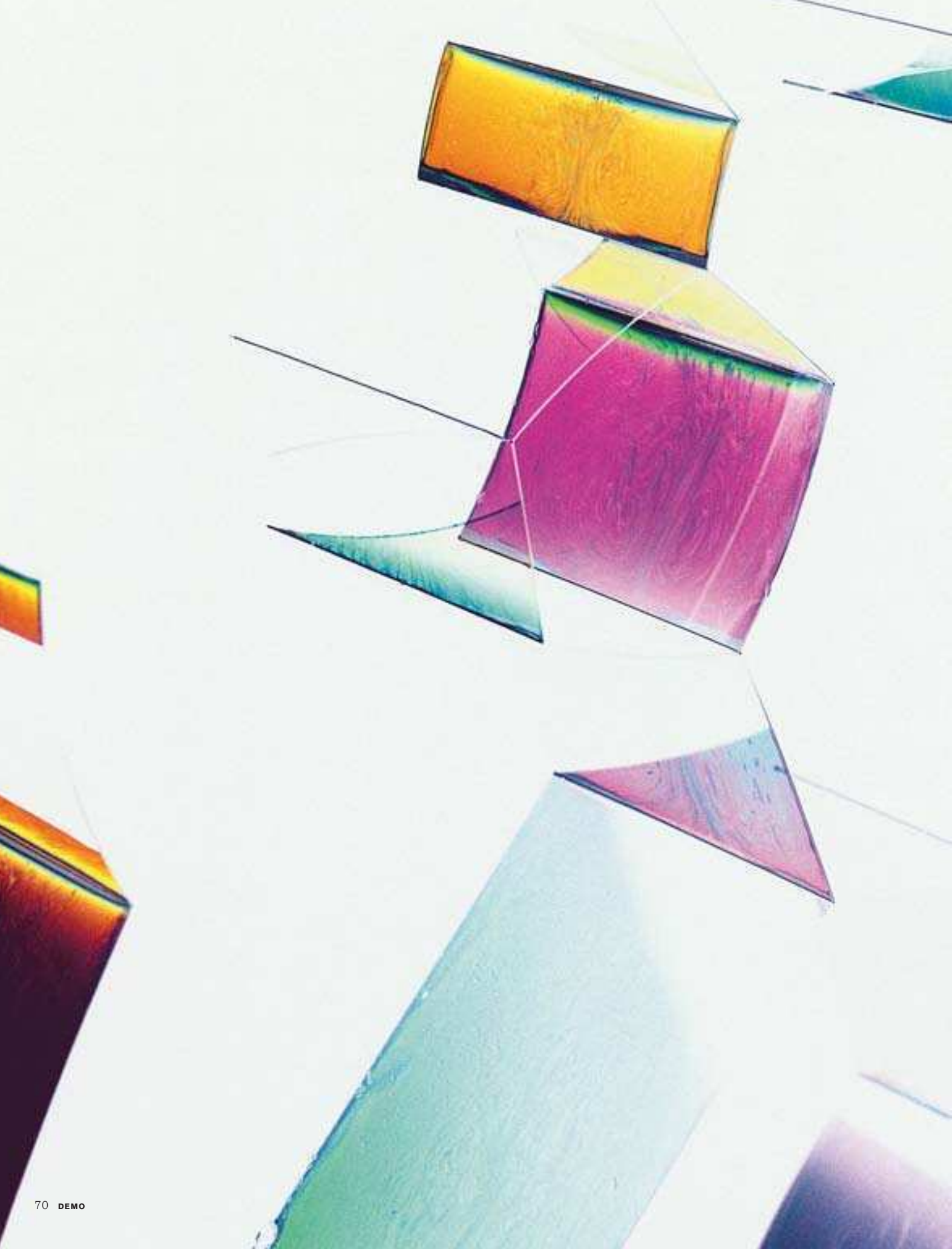
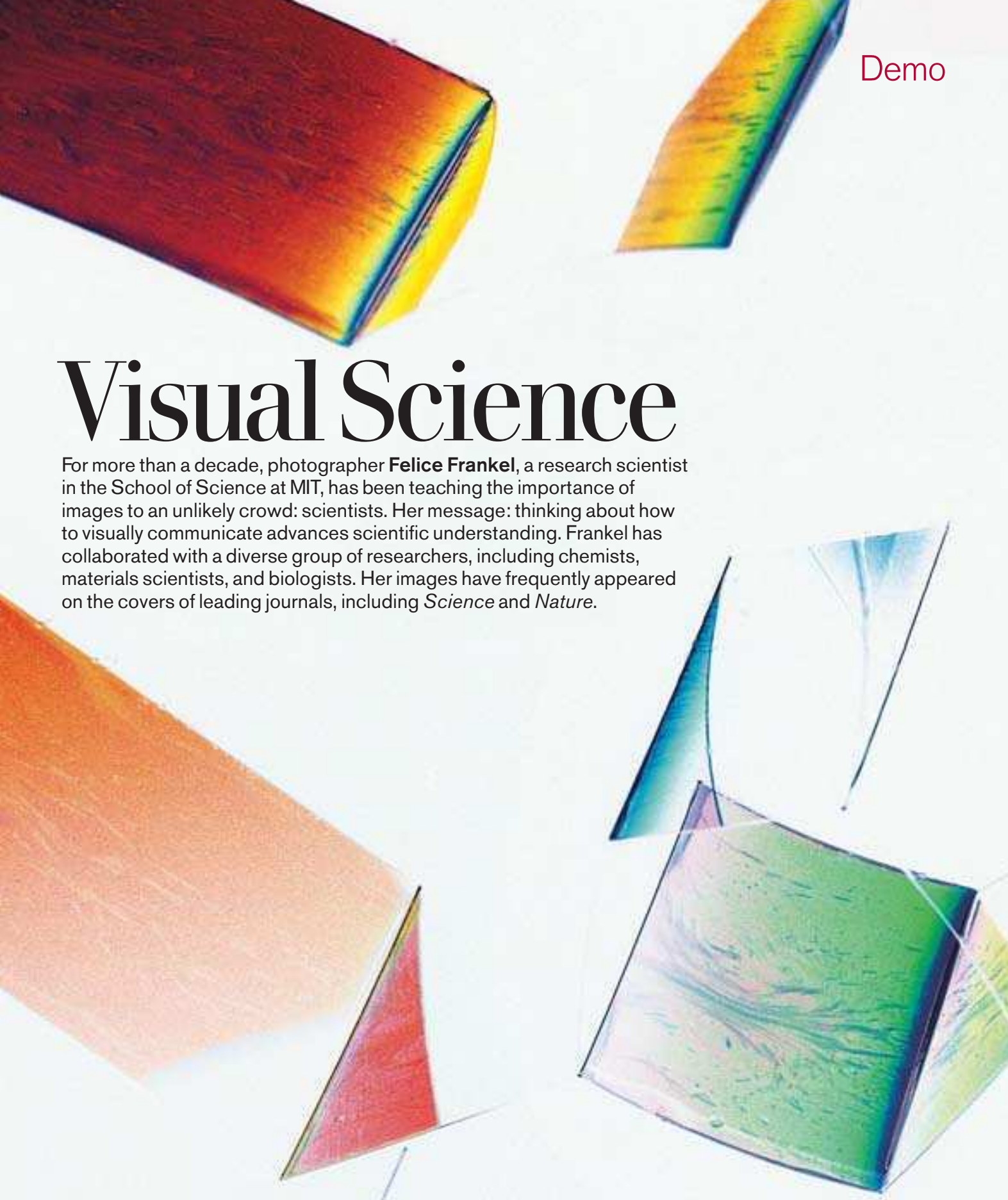
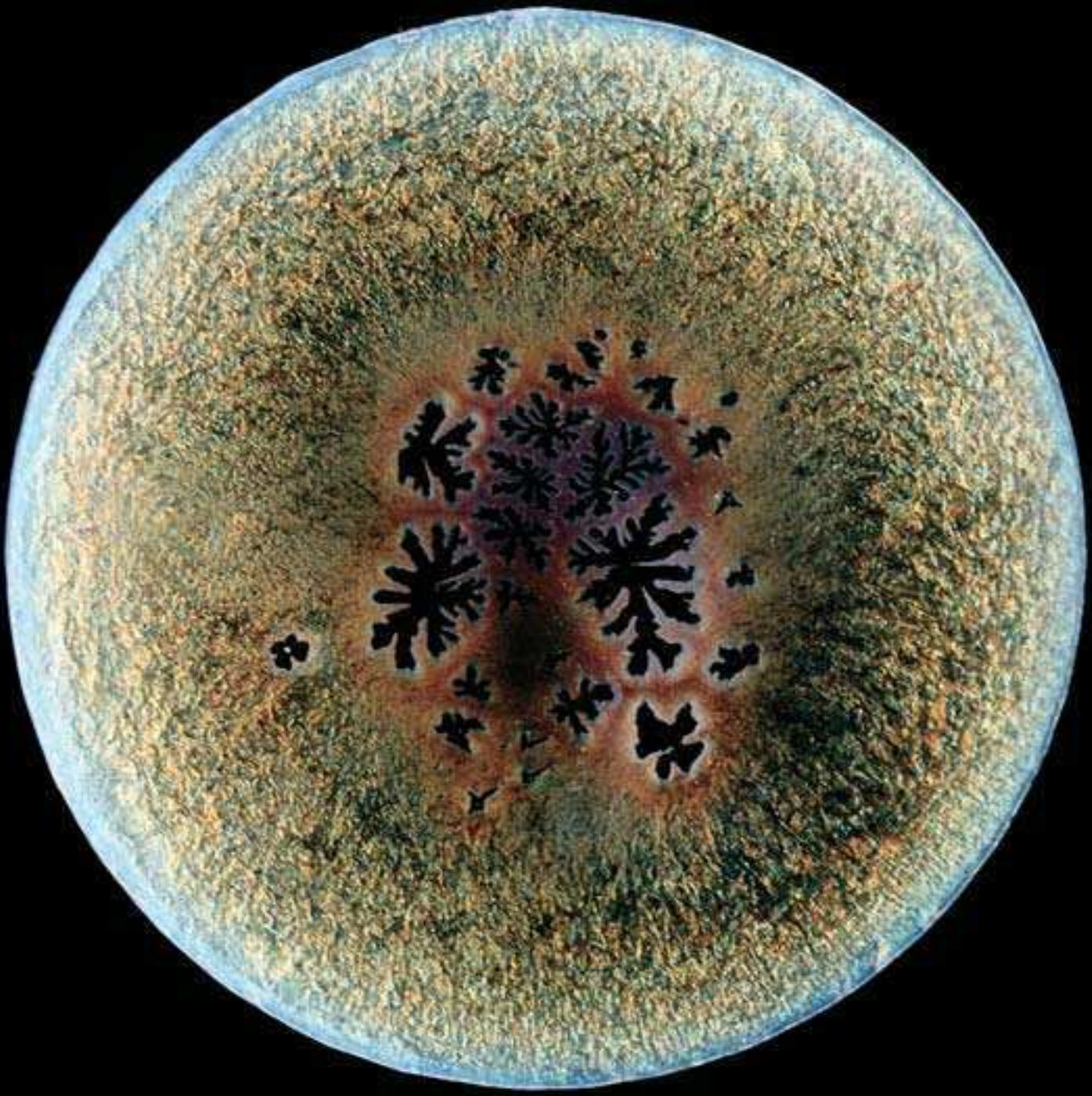


Visual Science

For more than a decade, photographer **Felice Frankel**, a research scientist in the School of Science at MIT, has been teaching the importance of images to an unlikely crowd: scientists. Her message: thinking about how to visually communicate advances scientific understanding. Frankel has collaborated with a diverse group of researchers, including chemists, materials scientists, and biologists. Her images have frequently appeared on the covers of leading journals, including *Science* and *Nature*.

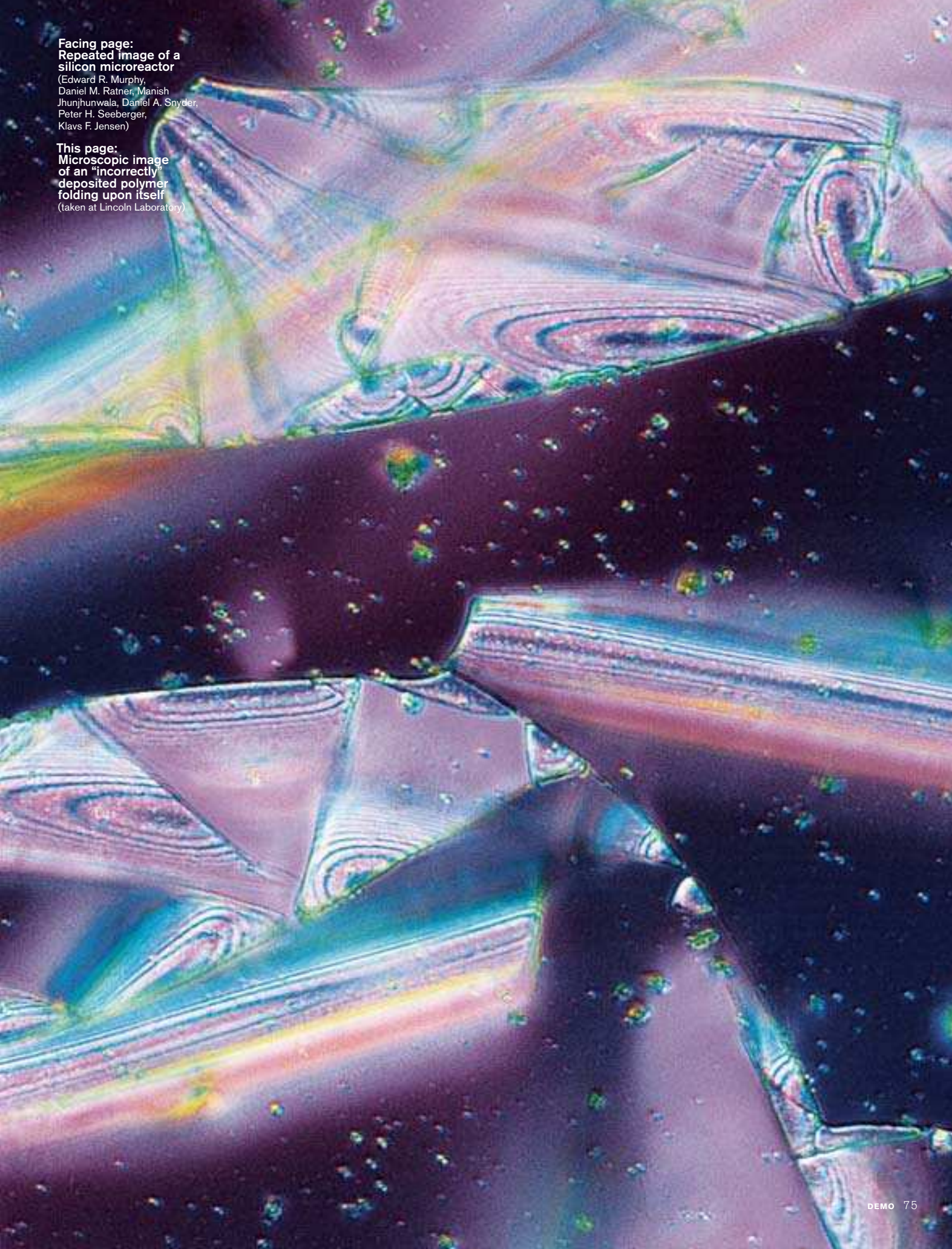


The interaction of the light reflected by the inner and outer surfaces of bubbles between sheets of glass produces complex patterns of color.



Facing page:
A block copolymer
(Jongseung Yoon, Wonmok Lee, Edwin L. Thomas)

This page:
A micropattern of calcite crystals formed by a self-assembly process
(Joanna Aizenberg, Andrew J. Black, George M. Whitesides)



Facing page:
Repeated image of a silicon microreactor
(Edward R. Murphy, Daniel M. Ratner, Manish Jhunjhunwala, Daniel A. Snyder, Peter H. Seeberger, Klavs F. Jensen)

This page:
Microscopic image of an "incorrectly" deposited polymer folding upon itself
(taken at Lincoln Laboratory)

Reviews

Our reviews use any artifact—a book, a product, a government report, a movie, a research paper—as the occasion for a contemplative essay on some technological controversy.

Cisco's Options Play

The company's proposed method for accounting for employee stock options would affect all of Silicon Valley.

BY ROGER LOWENSTEIN

If you were working in Silicon Valley in the 1990s, you probably have employee stock options to thank for your Porsche, your second home, and the gratitude of your spouse. If, more recently, you lost your job, you can thank stock options for that, too. The long debate over whether companies should be forced to account for options is really a debate about what sort of high-tech industry one wants. Will honest bookkeeping tame the goblins of extreme greed that bring bubbles and busts? Or as the ardent champions of options have long maintained, will accounting for options so flatten entrepreneurial zeal as to snuff out serious investment in the Valley?

Cisco Systems' newly proposed plan for valuing its employee stock options has at least introduced a novel idea into a debate that has flared since the early 1990s. Corporate watchdogs have insisted that employee options represent a cost to the public companies that issue them—and that the cost should be properly expensed in financial statements. Those on the other side—who come mostly from the high-tech industry—have argued that the obligation to account for options would discourage companies from granting them and thus diminish a primary method by which the industry attracts talented employees.

This dispute would seem unimportant, if only the stakes were not so high. According to Jack Ciesielski, publisher of *The Analyst's Accounting Observer*, by failing to book the costs of options, high-tech companies in the S&P 500 inflated their profits last year by 31 percent. The U.S. Securities and Exchange Commission recently ruled that companies must begin accounting for options in their first fiscal year after June 15, 2005. That hasn't quelled the controversy. A bill before the U.S. Congress would reverse the SEC mandate, and William Donaldson, the SEC chairman who pushed for the expensing rule, resigned in June. His proposed replacement, Christopher Cox, a congressman from Newport Beach, CA, has been a fervent opponent of expensing. (Hearings to confirm Representative Cox are expected soon.)

What Cisco is proposing has the appearance of a compromise. To understand this, you need to think a little about how options work—in particular, the options that companies such as Cisco grant to their executives and their ordinary employees.

From the point of view of the recipients, options are free. But as Alan Greenspan and Warren Buffett have observed, they aren't "free" in an economic sense. Like other forms of compensation, options bear a cost to the corporation. But what is that cost?

An option conveys the *right* to purchase a given number of shares at some specified price (called the strike price) within a specified time frame. If the stock rises above the strike price, the option's owner can exercise the option—that is, purchase shares from the corporation—at a price that is now below-market, and thus turn a profit. Frequently, to restrain dilution, the issuer will go into the marketplace and buy back shares—paying, of course, the market price. In the 1990s, corporations such as Microsoft and Cisco spent hundreds of millions of dollars on such buybacks.

On the other hand, if the stock price does *not* rise, then the option will expire worthless. Since every future stock price represents a different potential outcome, the number of such potential outcomes is limitless. And since we can't know in advance what the stock will do, the value of the option *at the time it's granted* must take into account the full range of possibilities.

Academics have been devising formulas to value stock options for decades; the creators of the Black-Scholes formula, the first such attempt to be widely adopted, won a Nobel Prize. Under Black-Scholes, the value of an option varies with the price of the stock, its volatility, the duration of the option, the dividend rate, and interest rates. But a good rule of thumb is that a 10-year option to buy stock at $100 is worth about $30 or $40 today.

The traders who help set prices on option exchanges are, of course, pragmatic, profit-motivated creatures who respond to supply and demand. But usually they also bear in mind the valuations that Black-Scholes would predict. And though option valuation formulas have at times failed spectacularly, they are good approximations for how most options trade most of the time.

However, Silicon Valley executives say the formulas overstate the value of employee options. Interestingly, dozens of corpora-

HOLLY LINDEM

tions, most of them outside tech (Microsoft is a big exception), have started to expense options voluntarily, and none of them seems to have a problem with using a standard formula.

But the bean counters in Silicon Valley have a point. Black-Scholes was developed for plain vanilla options that trade on exchanges. Employee options cannot be bought or sold, and under certain conditions (if the employee quits or is fired, for instance) they are cancelable. Therefore, it is reasonable to suppose that such options are worth less than vanilla. But how much less?

Cisco's solution would delight Adam Smith. Instead of using a formula to derive a value, the company plans to issue new derivatives, similar to the options granted to its employees, and to sell these derivatives to willing buyers. The price that the buyers pay would represent the true "cost" of the employee options.

Morgan Stanley, Cisco's investment banker, has been peddling the plan to scores of other companies in the Valley and elsewhere, so it's likely that Cisco will not be alone. But first, it will have to get a green light from the SEC, which has been studying the proposal since late spring, and whose decision is being eagerly awaited in the Valley.

At least in theory, the SEC is amenable to a free-market approach, and so is the Financial Accounting Standards Board (FASB), a private-sector body that sets the accounting rules that the SEC enforces. A FASB bulletin on options notes, "observable market prices…in active markets are the best evidence of fair value and, if available, should be used as the basis for measurement." The key phrases are *in active markets* and *if available*: no "active market" for employee-like stock options has ever existed. But the idea of creating one had occurred to Buffett, who sits on the board of Coca-Cola, which has expensed options since 2003. As Buffett told me, "That was our original idea at Coke. It's the most rational approach, as long as it isn't gamed."

Coca-Cola went with Black-Scholes, perhaps because the stakes were not so large. But the stakes at Cisco are very large. Last year, Cisco granted 195 million options, far more than any other single corporation in the S&P 500 (Coke granted 31 million). Also, according to Ciesielski, Cisco's unwillingness to expense inflated its earnings 38 percent last year. By contrast, options reduced Coke's earnings by only 5 percent.

The difference reflects the chasm that has separated mainstream America from Silicon Valley ever since the late 1960s, when a group of underpaid engineering whizzes broke away from Fairchild Semiconductor. Their disenchantment stemmed, in part, from Fairchild's resistance to the idea of granting employees stock options; in the company they created, Intel, options would become as much a part of employee culture as the union shop steward is at General Motors. Even today, high-tech companies, which need a means of luring and retaining ambitious employees, rely on options much more than other sorts of companies.

In the 1990s, the theory that options drove corporate returns gained wide currency and—coupled with the realization of what they could do for CEO pocketbooks—led to a boom in option grants. FASB proposed a rule that options should be expensed, but VIPs in the Valley, led by venture capitalist John Doerr, kicked up a furious protest. In 1994, Arthur Levitt, then chairman of the SEC, bowed to political pressure and urged FASB to back down. He would later call that decision his worst mistake.

Levitt's surrender has been portrayed by people on both sides of the debate as the defining moment of the Roaring '90s. In the view of critics such as Joseph Stiglitz (and me), indulging the fiction that options were "free" led to grossly excessive grants. This distorted proper incentives, leading to mismanagement and scandal. On the other hand, many executives have argued that without the ability to recruit top talent that options engendered, the high-tech boom might never have occurred. In this view, presumably, the bust was a small price to pay—even though it deflated the Nasdaq by close to 80 percent.

Given how much the Valley has at stake, we should at least be circumspect about accounting "compromises" emanating from the left coast. Cisco, in particular, has been a self-interested advocate. In the 1990s, John Chambers, the company's CEO, lobbied vociferously against expensing. And no one at Cisco stood to lose more from it. During the last four years of the boom (1996 to 1999), Chambers received option grants of, successively, 1.6 million shares, 1.8 million, 1.4 million, and 2.5 million. No one can say for sure whether the potential lucre that such options represented was a factor in Cisco's decision to try to grow so rapidly—too rapidly, as it turned out. All we know is that the options existed, that Cisco's managers stood to make millions on each increment of stock price appreciation, that during the late 1990s Cisco placed huge equipment orders, and that in 2001 it was forced to write off $2.25 billion worth of that equipment. Its stock collapsed, too—from $80 in 2000 to $8 in 2002.

However, it is also possible to see Cisco as an options success story. Even its post-bubble low of $8 a share was 100 times the going-public price of 1990. By any fair reckoning, the net result of the boom and bust of the tech industry was also strongly positive.

Chambers has not lost his ardor for options. In both 2002 and 2003, he received an enormous new grant of four million shares. Then, in 2004, when it became clear that expensing was coming, Cisco, along with Qualcomm and Genentech, proposed a valuation formula that seemed absurdly lax. As FASB noted, "the proposed method can be easily designed to produce a value of zero."

This is when Cisco turned to Morgan Stanley to design an option look-alike to sell to investors. What has Morgan wrought?

The instrument is a "warrant" that would be sold to investors. Suppose that in June 2006 Cisco granted a new batch of employee options. It would also sell to investors warrants that had the same terms as the options—including that they be nontradable.

Given how much the Valley has at stake in the way options are accounted for, we should at least be circumspect about "compromises" emanating from the left coast.

In theory, the holders of the warrants would get the same return as the employees. So whatever investors bid for the warrants would determine the value of the options.

Cisco intends to sell the warrants in an auction, but the auction would probably be open only to a dozen or so institutional bidders, which Cisco (or perhaps Morgan Stanley) would preselect. This has raised concerns. Since when did limiting the number of potential bidders lead to the most accurate price?

What's more, the fact that the warrants could not be traded will presumably greatly limit the demand for them. "You are talking about a very idiosyncratic contract," notes Myron Scholes, one of Black-Scholes's Nobel laureate creators. "The Cisco management team must know a lot more about HR [human resources] at Cisco than the outside investors. Due to that, [investors] would probably insist on a large discount." (Knowing, for instance, whether an executive who had been granted a lot of options was planning to leave the company before being able to exercise those options would matter; if her options expired worthless, so too would a proportionate amount of warrants.) Scholes says the new instrument would likely produce an artificially low value. This would fulfill the apparent aim of Cisco's executives, since the lower the assessed cost of the stock options it grants, the smaller the effect on its reported earnings.

That the SEC has similar concerns became evident in June, when Chester Spatt, the agency's chief economist, worried aloud in a speech at Carnegie Mellon University that "barriers to transferability" might unduly depress the estimated values of stock options. Corporations have disputed this, noting that employee options cannot be traded either. The SEC has yet to decide, and the hope of high-tech executives is that the incoming SEC chairman will be faithful to his constituency. Investors should hope, more neutrally, that the SEC sticks to the decision to require expensing and then quickly embraces some market instrument that attaches to options a reasonable cost. That will result in *some* expense on Cisco's books, one that a free market has validated, and in some penalty against its earnings the next time it decides to award its CEO four million options. Ultimately, the existence of a financial deterrent is more important than its precise amount. And the option issue needs to be put to rest. ■

Roger Lowenstein contributes to the New York Times *and other publications. His most recent book is* Origins of the Crash.

SEAN MCCABE

Roamin' Holiday

GPS phones promise to change the way we think about location.

BY WADE ROUSH

37° 48.325' N, 122° 24.343' W, +30 meters altitude. That's the location of my desk in *Technology Review*'s San Francisco office. Just enter the coördinates into your cell phone, and it'll take you right to me.

Unless, of course, you don't have access to your phone's built-in navigation features. Many new phones use the Global Positioning System (GPS) to determine their coördinates, which can then be transmitted to 911 operators in an emergency. But Sprint and Verizon Wireless, which both sell handsets with built-in GPS chips, have not yet given outside software developers access to this same location information. So GPS navigation tools and related location technologies that ought to be standard features in today's phones remain far-off dreams for most cell-phone owners. Of all the major carriers in North America, only Nextel offers phones with user-accessible GPS functions.

Over time, that will change. The cell phone is the one computing and communications device that consumers carry everywhere they go, and as soon as enough people see their Nextel-toting neighbors enjoying GPS navigation and other location-driven services, cellular carriers and phone manufacturers will bow to consumer demand.

Imagine leaving your car at home and networking with other GPS-phone users to form impromptu car pools, or receiving Web pages on your phone about Pickett's ill-fated charge as you amble up Seminary Ridge in Gettysburg. Geo-aware devices that trigger location-specific services will become as natural as the very idea of wirelessness, and the Web itself will cease to be a placeless cyberspace and will be pinned at millions of points to the physical world we inhabit.

Meanwhile, though, I wanted to get a sense of what Nextel customers can do with the technology today. So I borrowed a couple of GPS-enabled Nextel phones and hit the streets of San Francisco to see how well they could handle everyday navigation tasks. For comparison, I also carried a dedicated GPS receiver I'd purchased a few weeks earlier.

A few words about the receiver. Having enjoyed the GPS navigation units in cars I'd rented in Canada and Germany, and having read with interest about the emerging sport of geocaching, I'd been pining for my own GPS unit for some time. I headed over to the local REI and splurged on a Garmin GPSmap 60C.

It's the company's flagship handheld unit, distinguished by a large color display that's remarkably bright even when the backlight is off. After spending a few hours with the instruction man-

ual, I felt ready to strike out on my first geocaching expedition. Geocaching is one of those outdoor sports that, like hang gliding, jet skiing, and rappelling, exist only because some tinkerer invented the right thingamajig. (For GPS, of course, we're indebted to the U.S. Navy and Air Force, who wanted a way to get ICBMs to their precise targets.) Geocachers hide camouflaged caches—typically, small ammo boxes or Tupperware containers holding logbooks and a few trinkets for visitors to take and replace—then publish their latitudes and longitudes on the Internet. Geocache hunters download these locations, called waypoints, to their GPS units and navigate to the caches using only the units' built-in compasses, maps, and range indicators.

Geocaching.com, the sport's leading website, lists more than 185,000 cache locations worldwide. I downloaded a dozen in San Francisco and neighboring Marin County and spent two successive Sundays striding about holding the Garmin unit out in front of me like a high-tech divining rod. Though I've lived in the Bay Area for almost eight years, the searches took me down streets and trails I'd never traveled before. The 60C showed me highly detailed maps, laid down virtual "bread crumbs" that I used later to reconstruct my journeys on my home PC, and was sufficiently sensitive to GPS signals to guide me to within about three meters of a given waypoint. From there, it was up to me to find the caches. In Sausalito, I found one squeezed into a film canister that was glued to the underside of a piece of driftwood. On Russian Hill in San Francisco, I spent half an hour scrounging for a cache that turned out to be hidden in plain sight under a very convincing plastic rock.

The frisson of finding a cache is obviously part of the sport's appeal, as is the fun of tramping through unfamiliar territory. But my guess is that some geocachers are also gadget freaks who, like me, marvel at the idea that a device the size of a chocolate bar can, in concert with a network of distant satellites, transform the abstract grid of latitude and longitude lines created by 19th-century astronomers and cartographers into something average folks can grab on to and utilize. Indeed, GPS is transforming geography in much the same way that mechanical clocks and watches regularized our once fluid experience of time. As soon as there were simple ways to measure time, we could organize our actions around specific moments; every school bell and factory whistle in the nation could sound at 8:30 A.M. The concept of synchrony set the stage for the 19th-century revolutions in industry and transportation. Similarly, now that we can easily measure latitude and longitude, we can organize our actions around specific locations. Adventurers can navigate to the same remote spot at different times, as in geocaching; businesses, artists, or historians can share online information about any physical thing using its GPS-supplied coördinates rather than a Web-type Uniform Resource Locator (URL). Call it "synlocality."

It all worked great, until I decided to outsmart traffic and zoomed a couple of exits past the phone's recommended turnoff to get to the mall.

But dedicated handhelds like the Garmin aren't the wedge technology for GPS: cell phones are. So how do today's GPS phones measure up? It depends on what you want to do with them. The Motorola i736, a jaunty red phone styled like Dale Earnhardt Jr.'s NASCAR racing car, was loaned to me by Trimble, a Sunnyvale, CA, company that makes GPS hardware and software. The phone came with Trimble Outdoors, a Java program that displays location information and links to maps and route-planning applications running on Trimble's servers.

Using Trimble Adventure Planner, a Windows program that I downloaded to my laptop, I created a set of waypoints for a walk around Telegraph Hill. The Adventure Planner program communicated via the Internet with Trimble's servers, which in turn transmitted a route and the corresponding map data to the phone. Once I went outside and obtained a GPS fix, the phone guided me from waypoint to waypoint via the on-screen compass. *(See www.technologyreview.com/gps for an illustrated travelogue of the trip.)* I found a few things troubling: the on-screen maps were too small to read comfortably; running Trimble Outdoors and other Java applications exhausted the device's batteries in a couple of hours; and the actual positioning seemed less precise than the Garmin's (the i736 could locate a waypoint only to within 10 meters or so—which isn't precise enough for geocaching). But for a casual hiker who would take a phone along anyway, the i736 is probably ideal.

Where-Aware Gadgets

Garmin GPSmap 60C handheld GPS receiver
$482 suggested retail price
$139 for basic North American road maps

Motorola i275 mobile phone for the Nextel network
$99 with a two-year service agreement
$10 per month for added TeleNav navigation service

Motorola i736 NASCAR Nextel Cup Series phone
$99 with two-year service agreement
$10 per month for added Trimble Outdoors Platinum GPS application

The i275 is another Motorola-Nextel phone, but thanks to preloaded TeleNav GPS software, the unit I tested was a very different beast. TeleNav, created by Televigation, which is also based in Sunnyvale, turns the phone into a credible substitute for an in-dash car navigation unit. I used it for a trip across town to San Francisco's Stonestown Galleria. I looked up the mall's address on Yahoo, called TeleNav's 800 number, and spoke the city and street names and the address aloud. TeleNav's servers interpreted my speech, calculated the best route, and transmitted turn-by-turn instructions to the phone. As I drove, the phone offered helpful spoken instructions like "Prepare to turn right." It all worked great, until I decided to outsmart traffic and zoomed a couple of exits past the phone's recommended turnoff. TeleNav was slow to determine its new position, and I was taking turns faster than it could calculate a new route. If I had actually been lost, this delay would have made matters worse. Full in-dash GPS units are more agile, in my experience. But the i275 got me to the mall in the end.

I wouldn't give up my Garmin for either of these phones. But for people who don't need to know their positions down to a thousandth of a minute, they're just fine. And even including a monthly subscription to TeleNav or Trimble Outdoors, they are relatively cheap. The $99 cell phone will bring GPS to Everyman—who will find uses for it everywhere. ■

Wade Roush is a senior editor at Technology Review.

Search inside the Book

A long-awaited book about Google is also about the "long tail."

BY MARK WILLIAMS

JOHN BATTELLE'S *The Search: How Google and Its Rivals Rewrote the Rules of Business and Transformed Our Culture* is a book that, when the contract for it was announced in 2002, was probably the most anticipated book with the most interesting subject and the hottest author in tech-business journalism. Still, books take a long time to write. Battelle—who founded the *Industry Standard*, a now defunct newsweekly that aspired to be the *Economist* of the dot-com boom but plummeted into bankruptcy in 2001—knew he had to maintain his status as pundit. So in fall 2003, he began blogging about writing *The Search*.

Battelle intended his Searchblog (battellemedia.com) to be not only a promotional device but also a vindication of his theories. Blogging would become part of the process of writing *The Search*, as readers responded to his postings with arguments and new ideas that would enrich the final book.

When I talked to him, Battelle said blogging about the book while writing it embodied one of its important themes: the shifting of power away from the old order—in this case, old media—as search and new Internet services allow information to be shared. "I like to call this the Force of the Many," Battelle says.

Battelle explains this force by retelling the history of Google. His main theme is how search will become the means by which people access every service or application that might run on a computing platform, as well as every possible species of data. "Search already is the spade by which we turn the soil of human knowledge," Battelle told me. "It's not 'the Web OS,' but it is our mainstream navigation interface." Battelle develops this line of reasoning in a fairly original way, and it has been his blog's consistent theme. (It has, of course, been much discussed elsewhere: see, for instance, Charles Ferguson's January *Technology Review* cover story, "What's Next for Google?")

But the heart of Battelle's story is the rise of the "search economy," which exists (he says) because search has allowed the commercial exploitation of "long tails." This idea is less original. The commercial implications of the Long Tail—in the context of e-commerce, it's become a proper noun—were made famous by *Wired*'s editor in chief Chris Anderson in an October 2004 article he wrote for his own magazine. Anderson is himself writing a book, *The Long Tail*, to be published next year. But any proprietary feelings he might have about long tails would be misplaced: like Battelle, he has been blogging his book into existence at www.thelongtail.com, and the term is now common currency.

Long tails are not original to Anderson either. The concept of the long tail will be familiar to anyone who has taken a statistics class. There are many common statistical distributions whose graphs show a small number of events occurring very often and a vast number of events (the long tail) occurring rarely. In aggregate, however, the rare events can outnumber the common events.

Battelle is interested in the application of search to untapped markets. In the context of e-commerce, long tails have three implications. First, via the Internet, products with little demand can, collectively, create a market exceeding that of the few bestsellers. Second, in the same way that it enables a proliferation of markets, the Internet enables a proliferation of vendors. Finally, thanks to search, a shift from mass to niche markets is likely.

Given the familiarity of Battelle's themes, his book's most interesting aspect may be how it was composed. How did Battelle weigh the potential benefits of blogging (dissemination, refinement, and expansion of the book's ideas) against the inherent disadvantages (loss of "freshness," potential for others to steal ideas)? Battelle responded, "The pros win. Folks will buy the book, I think, because people they trust recommend it. Those folks are my readers on the blog, I hope."

Despite their familiarity, the ideas in *The Search* are important and real. Battelle is a clear and forceful writer. The blog-powered process that he (and Anderson) are using may be an effective way to refine ideas and ensure their survival. But to judge by Battelle's book, successfully blogging a book has this unintended consequence: by the time the book is published, your most receptive audience may find your ideas a little stale. ■

Mark Williams is a contributing writer at Technology Review.

A Tale of Two Blogs

The Search: How Google and Its Rivals Rewrote the Rules of Business and Transformed Our Culture
By John Battelle
Portfolio, 2005, $25.95

The Long Tail: A Public Diary on the Way to a Book
By Chris Anderson
www.thelongtail.com

PHOTOGRAPH COURTESY OF PENGUIN GROUP

There's the Rub

Convenience comes with baggage.

We know resistance when we feel it. And we're well aware that reducing physical or social inefficiencies can produce big benefits; Jacqueline Krim of North Carolina State University is a pioneering physicist who studies friction and says the U.S. could save $110 billion a year by limiting it. Yet large-scale improvements in efficiency bring out unexpected collective behavior that may introduce new sources of social, if not of physical, friction.

Consider luggage. In the late 1980s, a pilot named Robert Plath borrowed the idea of the in-line skate to develop the first commercially successful wheeled suitcase. Today, most new luggage can roll. For soft cases, the conversion was simple. Not so for some premium models. Halliburton aluminum luggage, which was invented by the oil well–cementing pioneer Earle Halliburton (but is now produced by an independent company, Zero Halliburton), is an incomparable made-in-the-U.S.A. suit of pressed aircraft-grade aluminum armor. It defies the ravages of human and mechanical abuse and is sealed with a neoprene gasket.

At last, the makers of my 30-year-old Zero Halliburton two-suiter have produced a replacement model, the Zeroller, with an elegantly recessed handle and polyurethane wheels. The price is still steep, $755 and up, but with the convenience of the Web I found excellent mail-order prices. And besides, the latches of my case were starting to wobble.

The problem with this convenience is social, not technical. The airlines, as the Baltimore *Sun* recently reported, have found that wheeled cases, which have grown in popularity since the early 1990s, have encouraged people to pack heavier bags. Facing higher fuel costs, most carriers have begun to impose a charge of at least $50 for bags weighing more than 50 pounds. Whether reasonable cost recovery or stealthy rip-off, the charges mean that the more durable—and thus heavier—the bag, the smaller the free payload. At 13 pounds, a 24-inch wheeled Zero Halliburton Zeroller uses more than a quarter of the domestic allowance; a 26-inch model, closer in capacity to my old two-suiter, weighs 16 pounds, nearly a third. And thus the convenience of wheeled luggage begins to break down. At airports, it is common to see travelers hastily removing heavy items from their luggage and dragging them onto planes in plastic bags.

The transfer of information is not so different from the movement of personal effects. Neither in principle requires nearly as much work as was once believed. In the case of data, the Web has trivialized the effort of searching for knowledge that was theoretically public but too tedious in practice to discover. The New York University communication scholar Siva Vaidhyanathan has even proclaimed "the collapse of inconvenience" to a Boston *Globe* writer, referring to the millions of Web users who employ the pitiless eye of search engines to hunt for awkward personal data, from youthful indiscretions to middle-aged eccentricities and worse.

In popular culture, too, the extension of efficiency to the masses has changed behavior unexpectedly. The CEO who did the most to encourage early television remote control, E. F. McDonald Jr. of Zenith, hated commercials and expected newly empowered, remote-armed viewers to force the replacement of advertising with subscription-based television. They of course did no such thing; even most premium cable channels now feature advertising. But restless viewers did change programming in other ways.

For decades, programmers have been increasing the pacing of their shows. This makes it less likely that viewers will change programs at any instant, but for many observers, the jumpier action makes the shows less effective. Our ability to avoid commercials by fast-forwarding effortlessly through our TiVo-cached and similarly stored programs is making product placement more pervasive.

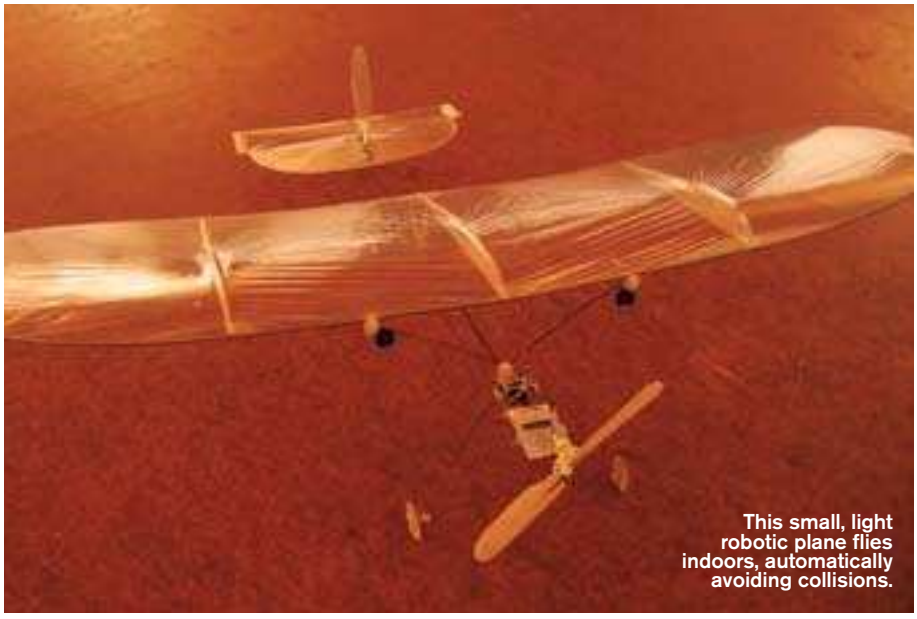
Finally, the spread of easy electronic fixes to knotty problems can postpone fundamental solutions. The ease of crafting new legislative districts with mapping software has invigorated the ancient art of gerrymandering. And a taxation expert, Joseph J. Thorndike, recently argued in the New York *Times* that electronic income-tax preparation software has removed an important incentive for tax reform: the annoyance of calculating certain taxes. If citizens had to fill out their forms manually to comply with the alternative minimum tax, originally directed at the wealthy but expected to soon snare a third of taxpayers, the tedium of the calculation (by many who turned out not to owe any tax) might have tipped the scales for reform.

I'm not about to do next year's form 1040 on an abacus, but sometimes a bit of inconvenience is just what I need; having a manual transmission discourages me from answering the cell phone while driving. As Vaidhyanathan observed, "It turns out inconvenience was a really important part of our lives, and we didn't realize it." ■

ERIC PALMA

From the Lab

A good place to look for the important technologies of tomorrow is in the scientific discoveries of today. Based on recommendations from academia and industry, *Technology Review* has chosen these peer-reviewed papers as ones that may one day inspire the development of those technologies.



This small, light robotic plane flies indoors, automatically avoiding collisions.

COURTESY OF JEAN-CHRISTOPHE ZUFFEREY

INFORMATION TECHNOLOGY

Flying Robot

Thirty-gram aircraft steers itself

RESULTS: Swiss researchers have built a robotic aircraft with an 80-centimeter wingspan that flew indoors for about four minutes, detecting walls and automatically turning away from them, thanks to two one-gram cameras, a gyroscope, and a small microcontroller onboard.

WHY IT MATTERS: Small robots that can operate inside buildings or in tight spaces like caves or tunnels may be useful for search-and-rescue, reconnaissance, and inspection applications. Researchers have previously tested larger flying robots outdoors with fewer obstacles and indoors doing limited maneuvers like landing. Here, Jean-Christophe Zufferey and Dario Floreano of the Swiss Federal Institute of Technology in Lausanne have shown that a smaller aircraft can fly indoors for a relatively long period of time while successfully avoiding collisions.

METHODS: The researchers made their aircraft out of carbon-fiber rods, balsa wood, and thin plastic film for the wings and tail. They mounted one video camera on the leading edge of each wing and connected the two cameras to a low-power microcontroller near the front of the aircraft, behind the motorized propeller. The microcontroller grabbed images from the cameras about 20 times per second and calculated how fast obstacles like walls appeared to be moving toward the aircraft. As objects got closer, the cameras saw them as moving faster. The microcontroller recognized a certain threshold speed as an indication that an obstacle was getting too close and sent signals to the rudder to turn the plane about 90 degrees.

However, the side-to-side movements of the plane's nose—its "yaw"—also affected the speed at which obstacles appeared to be approaching, confusing the plane's obstacle avoidance system. To counter this effect, the researchers placed a gyroscope behind the propeller that measured its yaw rotation speed. The microcontroller took this data into account when analyzing the camera images.

The researchers tested their obstacle avoidance algorithm on their aircraft in a 256-square-meter arena. The walls of the arena were made of wide vertical strips of black and white cloth to enhance the contrast of the obstacles and make them more visible to the cameras. The researchers controlled the plane's altitude manually with a joystick and a wireless connection.

NEXT STEP: The researchers are working on a 12-gram, 40-centimeter-wingspan aircraft with lighter and smaller electronics so that it can fly in smaller rooms. They are also integrating an automatic altitude-control system into their plane to make it fully autonomous. And they are putting more-sensitive cameras on board, so the plane can detect obstacles that don't have high-contrast coloration. **Corie Lok**

Source: Zufferey, J.-C., and D. Floreano. 2005. Toward 30-gram autonomous indoor aircraft: vision-based obstacle avoidance and altitude control. *Proceedings of the IEEE International Conference on Robotics and Automation 2005*, pp. 2605–2610.

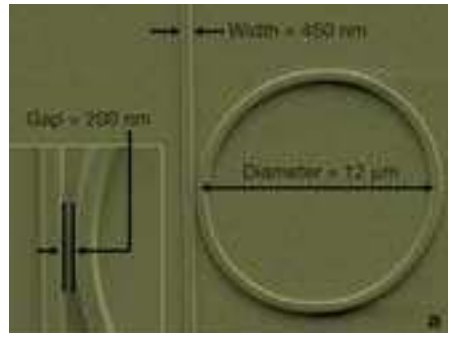
Mini Modulator

A key device for silicon optics gets tiny

RESULTS: In an important step toward integrating optoelectronics into silicon chips, researchers at Cornell University have fabricated a silicon modulator—a device that converts electronic signals into optical ones—roughly 12 micrometers wide, about a thousand times smaller than previous silicon electro-optical modulators.

WHY IT MATTERS: As chip makers pack more transistors on silicon, problems such as heat generation from electrical resistance and electrical interference between closely spaced wires threaten to degrade performance. Many believe that optical connections—which transmit information in the form of light pulses instead of electric current—offer a way around these limitations. Researchers have long been striving to produce optical devices that can be easily integrated into silicon *(see "Intel's Breakthrough," July 2005)*. Electro-optical modulators are vital to this plan, but current silicon versions of them are too large to fit easily onto a chip. The dramatic drop in size that Michal Lipson and her colleagues demonstrated makes a chip-based modulator seem more feasible.

METHODS: To build their modulator, the Cornell researchers etched a small piece of silicon to form a 12-micrometer-diameter, 250-nanometer-tall raised ring. They positioned this ring next to a straight ridge, known as a waveguide, just 450 nanometers wide. A beam of laser light traveling down the waveguide will either pass the circular section—the "ring resonator"—without interacting with it or be diverted into it, depending on the wavelength of the light. The refractive index of the silicon and the circumference of the ring determine what wavelength of light the resonator diverts. Applying a voltage from the interior of the ring to the area just outside it creates free electrons and positively charged "holes" within the ring that change its refractive index. By using a varying voltage to either shutter light or let it pass through the waveguide, the researchers encoded information onto a laser beam at a rate of 1.5 billion bits per second.



A silicon modulator that converts electronic signals into optical ones, imaged by a scanning electron microscope. Inset: a close-up view of the gap between the two components, the ring resonator and the waveguide.

NEXT STEP: The researchers believe that their device will be able to modulate signals at more than five billion bits per second, once they make some refinements, such as improving the electrical contacts that supply the input signals from the rest of the circuit. **Dan Cho**

Source: Xu, Q., et al. 2005. Micrometre-scale silicon electro-optical modulator. *Nature* 435:325–327.

Greater Graphics

Chip renders high-quality images in real time

RESULTS: Researchers from Saarland University in Saarbrücken, Germany, have developed a prototype chip that can render desktop computer graphics in real time using a sophisticated technique called ray tracing. Ray tracing produces more-realistic and higher-quality graphics than other techniques, but it previously required a cluster of PCs for real-time performance. Now, the researchers, led by Philipp Slusallek, have shown that a single chip can use ray tracing to render simple scenes at 20 frames per second. (The frame rate for movies, television, and video games ranges from 24 to 30 frames per second.) The chip rendered more-complex scenes at fewer than 10 frames per second.

WHY IT MATTERS: The conventional computer-graphics rendering method, called rasterization, doesn't handle shadows or reflections well, resulting in lower-quality images. Ray-tracing algorithms simulate the physics of light more accurately and make complex scenes look more realistic. But on a single computer, they can take several minutes or even hours to render one image. By implementing the algorithm on a chip, the researchers have provided a way for one PC to do the job in real time, making high-quality rendering cheaper and feasible for home computers.

METHODS: The researchers designed a new architecture for their chip that is optimized for the ray-tracing algorithm. They arrived at their design by experimenting with chips called field-programmable gate arrays, which can be reconfigured into different circuit patterns. They then used their chip, running at 66 megahertz, to render 11 different scenes, some taken from computer games and some that were standard scenes used by graphics researchers. They measured such performance characteristics as how many frames the chip generated each second.

NEXT STEP: With the chip's design finalized, the researchers will use more-standard integrated-circuit techniques to build a new version that can accommodate more processors and render complex scenes faster than 10 frames per second—and that can be cheaply mass-produced. To adopt real-time ray tracing, computer-game programmers would need to slightly change the way they build the graphics for their games. **Corie Lok**

Source: Woop, S., J. Schmittler, and P. Slusallek. 2005. RPU: A programmable ray processing unit for realtime ray tracing. *ACM Transactions on Graphics* 24:434–444.

BIOTECHNOLOGY

New Map for Gene Hunters

Midsize DNA variations could aid in search for disease genes

RESULTS: Researchers led by Evan Eichler of the University of Washington have made a map of specific types of variation in the human genome, many of which had

COURTESY OF MICHAL LIPSON

never been documented before: insertions, deletions, and inversions of pieces of DNA, the majority of which ranged from 8,000 to 40,000 letters long. By comparing the genomes of two people, they found 297 sites of such variations, including 139 insertions, 102 deletions, and 44 inversions. When they compared these sites to 16 that had been previously documented, they found that their map had identified seven of them, most of which were associated with disease risk or drug sensitivity. This suggests that more of these newly discovered variations may play a role in disease or drug response.

WHY IT MATTERS: To find disease-causing genes, researchers need maps showing the locations of genetic variations between individuals. In the last few years, researchers have been mapping single-nucleotide polymorphisms (SNPs), one-letter changes in the DNA sequence, both individually and in sets of thousands that occur together. Researchers have also identified much-larger-scale genomic differences between individuals but hadn't yet mapped intermediate-size variations such as insertions, deletions, and inversions. To do a comprehensive search for disease genes, researchers need to look at all types of variation. This new map can help them do that.

METHODS: The researchers compared the reference human genome decoded in draft form in 2001 with the genome of a second person. This second genome was in the form of a library of one million pieces of DNA, each 40,000 letters long. The researchers sequenced 500 letters on each end of each piece and looked for matching sequences in the reference genome using bioinformatics software. By looking at the distance between two 500-letter-long sections of DNA in the reference genome, which corresponded to the two ends of one piece from the second genome, the researchers could tell whether an insertion or deletion had occurred between them. If the two 500-letter-long sections were in reverse order, that indicated an inversion.

NEXT STEP: The researchers would like to make their map more complete by comparing not just two genomes but 10. They are also developing tests that can quickly identify which variations occur in particular patients. Other researchers could then use these tests to compare the genomic variations of thousands of healthy and diseased individuals to find genes that may be contributing to the disease. **Corie Lok**

Source: Tuzun, E., et al. 2005. Fine-scale structural variation of the human genome. *Nature Genetics* 37:727–732.

Stopping Cell Death

Molecule lessens stroke damage via a new biochemical pathway

RESULTS: Harvard Medical School researcher Junying Yuan and colleagues have discovered a molecule that prevented a type of cell death in human cell cultures and lowered the amount of brain damage caused by stroke in live mice by 30 percent. The study suggests that some cases of cell death thought to be the uncontrollable result of injury or disease are instead regulated by a molecular pathway.

WHY IT MATTERS: Researchers have long known of one form of regulated cell death called apoptosis. This is a helpful type of cell death that prevents cancer and contributes to early development. Yuan's research demonstrates the existence of another type of programmed cell death that she and her team call "necroptosis." This process may be involved in brain trauma, heart attacks, stroke, and other diseases. In showing that necroptosis is the result of a programmed set of steps that a chemical can interrupt, Yuan's work suggests the possibility of new drug therapies to combat these diseases.

METHODS: In order to find an anti-necroptosis molecule, the researchers tested 15,000 chemicals concurrently in cells grown in separate wells. Yuan's team induced cell death and examined which chemicals prevented the cells from dying. Once they found a promising compound, they administered it to live mice whose brains had been temporarily deprived of blood, and compared the resulting damage to that induced in a control group.

NEXT STEP: Yuan and her team have discovered eight other necroptosis-blocking molecules and are using them to identify the steps in the necroptosis pathway by observing how each molecule affects dying cells. They are also seeking funding to develop a drug therapy for stroke based on their findings. **Kevin Bullis**

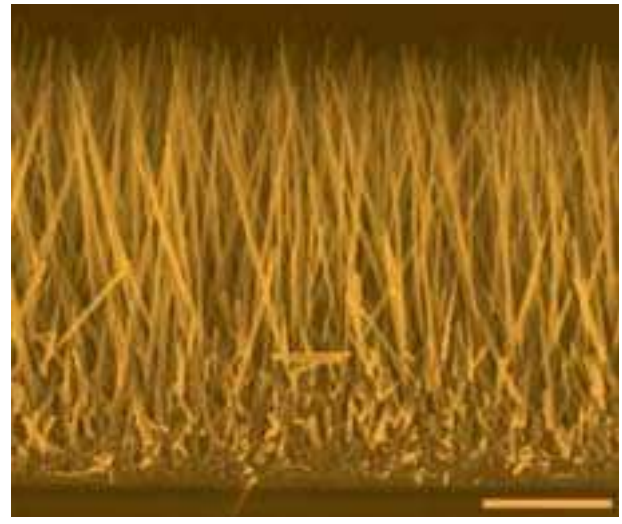
Sources: Yuan, J., et al. 2005. Chemical inhibitor of nonapoptotic cell death with therapeutic potential for ischemic brain injury. *Nature Chemical Biology* 1:112–119.

NANOTECHNOLOGY

Nanowire Solar Cells

Building photovoltaics out of nanowires

RESULTS: In a step toward cheaper and more efficient solar cells, researchers from the University of California, Berkeley, have made solar cells out of billions of nano-



Cross section of a nanowire array that forms the heart of a nanowire solar cell, imaged by a scanning electron microscope. Scale bar: 500 nanometers.

COURTESY OF PEIDONG YANG

wires, each wire about 60 nanometers in diameter and 20 micrometers in length. The nanowires, made of zinc oxide and coated in a light-absorbing dye, conducted electrons from one end of the cell to the other about 100 times more efficiently than other nanoparticle-based solar cells currently under development. The solar cells' overall light-conversion efficiency, however, was a relatively poor 1.5 percent.

WHY IT MATTERS: Silicon-based solar cells are expensive to make. Replacing the silicon with nanomaterials promises to lower costs. But the sunlight conversion efficiency of nano solar cells is typically low, mainly because electrons have to find their way to the external circuit by hopping between nanoparticles within the cell. Some electrons get lost along the way, leading to low light conversion efficiency. By replacing the nanoparticles with long single-crystal nanowires that run between the cell's electrodes, the researchers were able to get the electrons moving through the solar cell more efficiently. This is an important advance that could ultimately lead to more-efficient nano solar cells.

METHODS: The researchers, led by chemist Peidong Yang, made nanowire arrays by coating a conductive glass surface with zinc oxide "dots" three to four nanometers in diameter. The dots served as seeds for the subsequent growth of the wires. Yang's team then immersed the glass in a solution of zinc oxide for 2.5 hours. A polymer in the solution controlled the rate and direction of the wires' growth, ensuring that they remained perpendicular to the surface of the glass. The researchers dipped the array in a dye solution, placed the array between two electrodes, and filled the internal space with a liquid electrolyte. They then shone light with the same spectrum as sunlight onto the cells and measured the electrical output.

NEXT STEP: Although the cells' electron transport was better, their overall light conversion efficiency was low compared to that of some nanoparticle-based solar cells (which have achieved efficiencies of up to 10 percent). Zinc oxide harvests electrons from the dye less efficiently than does titanium dioxide—a material more commonly used in nano solar cells. The researchers are now making their nanowires out of titanium dioxide, a more challenging manufacturing process. The nanowires also have a smaller surface area than a network of nanoparticles, so they carry less light-absorbing dye. The researchers are consequently shrinking their nanowires to 10 nanometers in diameter so that they can fit more nanowires onto their arrays and increase the total surface area. Yang predicts that with thinner and more numerous titanium wires, his team will be able to achieve a conversion efficiency of 10 percent or more, which could make these nano solar cells a viable source of energy. **Corie Lok**

Source: Law, M., et al. 2005. Nanowire dye-sensitized solar cells. *Nature Materials* 4:455–459.

Tiny microcapsules self-assemble from a mixture of a salt, an organic polymer, and silicon dioxide nanoparticles in water. Left and middle: scanning electron microscope images of different microcapsules made from different salts. Right: a transmission electron microscope image of the same microcapsules shown in the middle image.

Making Microcapsules

Tiny chemical carriers form themselves

RESULTS: Chemical engineers have developed a simple "mix and shake" technique for producing microcapsules—tiny shells that can hold substances such as drugs and medical imaging dyes. The technique, developed by a team at Rice University led by Michael Wong, resulted in microcapsules measuring less than a micrometer across.

WHY IT MATTERS: With microcapsules, researchers can more precisely control where, when, and in what quantities a substance is delivered and released. One current production method, which relies on meticulously depositing a coating onto a core that is then dissolved away, has produced stable microcapsules a few micrometers across. But this method is expensive to use because it requires carefully controlled conditions, such as very low pressures and high temperatures, and harsh chemicals. The Rice method works at room temperature and atmospheric pressure, and uses water as a solvent. It's also simpler than other methods and potentially cheaper to use on a large scale.

METHODS: The Rice recipe for microcapsules begins with a mixture of water and the chemical to be contained in the shells, such as a small-molecule drug. The researchers then add a salt and an organic polymer that, when mixed, form water-permeable globules. Next, the researchers pour in silicon dioxide nanoparticles about 100 times smaller than the globules. The particles stick into the walls of the globules, forming capsules that trap the chemical and water mixture inside. By adjusting the mixing intensity and the quantities and types of salts, polymers, and nanoparticles used, the researchers varied the thickness of the capsule walls and the size of the capsules, changing the timing and rate of the release of the contents.

NEXT STEP: This method produces only grams of the shells at a time, and they are of nonuniform size. The team is now working on ways to produce the capsules by mixing the components in the form of individual streams of liquid. This would enable the continuous production of more consistently sized capsules. **Stu Hutson**

Source: Rana, R., et al. 2005. Nanoparticle self-assembly of hierarchically ordered microcapsule structures. *Advanced Materials* 17:1145–1150.

MIT MEDIA LAB

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Media Laboratory / Media Arts and Sciences Program

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Please forward nominations and expressions of interest in confidence to:
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William Holodnak and Nancy Martin at J. Robert Scott, executive search consultants and a Fidelity Investments company, are assisting the MIT Media Lab, medialab@j-robert-scott.com.

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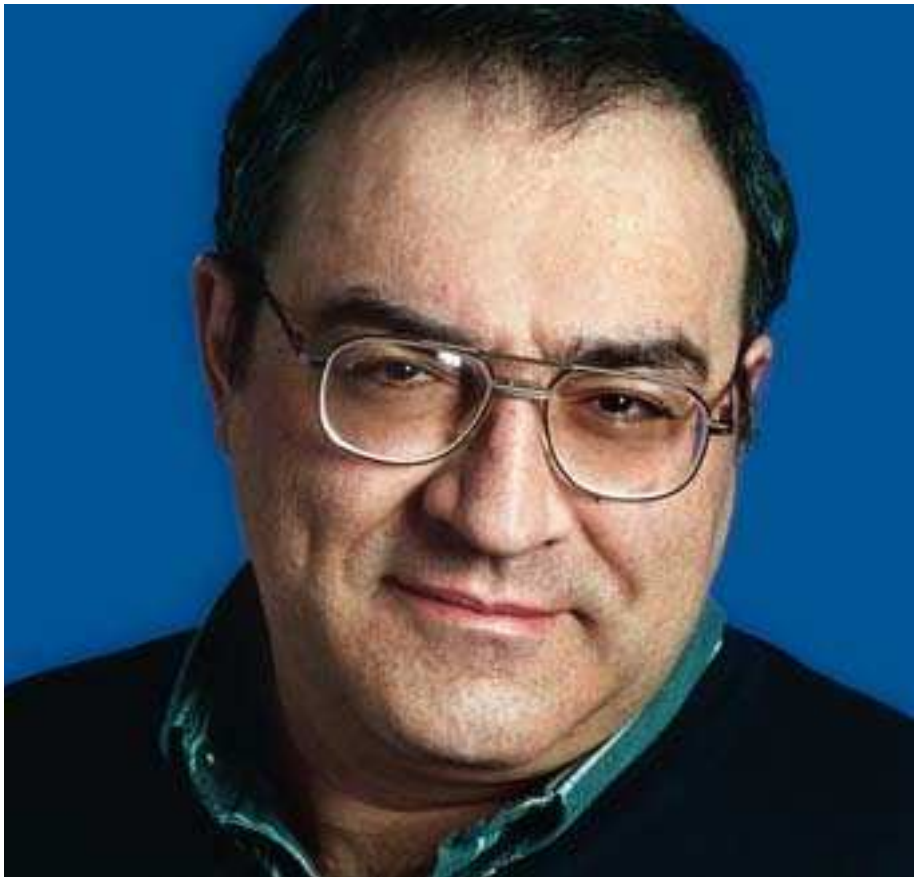

Mystery Man

An obscure Russian mathematician named Leonid Khachiyan changed how we allocate resources.

BY ANDREW P. MADDEN

Leonid Khachiyan, a Russian mathematician and a professor at Rutgers University who published a groundbreaking theorem in 1979 that helped advance the field of linear programming, died April 29 at the age of 52. Khachiyan's breakthrough, applying an approach known as the ellipsoid method to linear programming, continues to aid computer scientists in their efforts to tackle the enormously complex challenges of scheduling and resource allocation in fields ranging from finance to telecommunications to the airline industry.

When Khachiyan first published his work on the ellipsoid method, he was a little-known 27-year-old mathematician studying computational mathematics at the Computing Center of the Soviet Academy of Sciences in Moscow. Though he published his findings in *Doklady Akademii Nauk*, the academy's well-respected journal, it wasn't until months later that two U.S.-based academics introduced his dryly entitled paper—"A Polynomial Algorithm in Linear Programming"—to a broader audience of computer scientists and theoretical mathematicians. After the findings were reported in *Science* in 1979, Khachiyan became a computer science celebrity.

The New York *Times*, which profiled Khachiyan's achievement in a November 1979 article entitled "Soviet Mathematician Is Obscure No More," called him "the mystery author of a new mathematical theorem that has rocked the world of computer analysis." Given the tensions of the Cold War era, Khachiyan's result prompted both excitement and alarm, recalls Michael Grigoriadis, a colleague of Khachiyan's at Rutgers, who was working for IBM in 1979. But the importance of his breakthrough escaped nobody in academia and industry. Grigoriadis remembers that IBM's CEO asked his research groups to assess Khachiyan's work and what it might mean to IBM.

Linear programming is a mathematical approach to resource allocation. It emerged in the 1940s, as the U.S. military struggled to address complex issues of wartime planning. George Dantzig, a graduate student in mathematics during World War II who was enlisted by the U.S. Air Force to help with logistics, laid the foundation for linear programming and introduced his "simplex method" in 1947. The simplex algorithm provided a practical approach to determining how a finite number of resources could be allocated in the most efficient way, and it is still used today.

A major departure from the prevailing thinking of that era, Khachiyan's ellipsoid method answered the open question about the complexity of linear programming and encouraged new avenues of research, said Grigoriadis. Khachiyan contributed significantly to the field of combinatorial optimization, whose applications include the efficient routing of data packets across the Internet to reduce overall delay and the management of complex trucking routes.

After establishing his academic credentials in 1979, Khachiyan spent the next decade in Russia, holding a series of positions at the Computing Center and at the Moscow Institute of Physics and Technology. Khachiyan finally came to the United States in 1989 for a visiting appointment at Cornell University's School of Operations Research and Industrial Engineering. He was then offered an appointment at the Rutgers Department of Computer Science, where he ultimately gained tenure in 1992. Khachiyan became a naturalized U.S. citizen in 2000. ■

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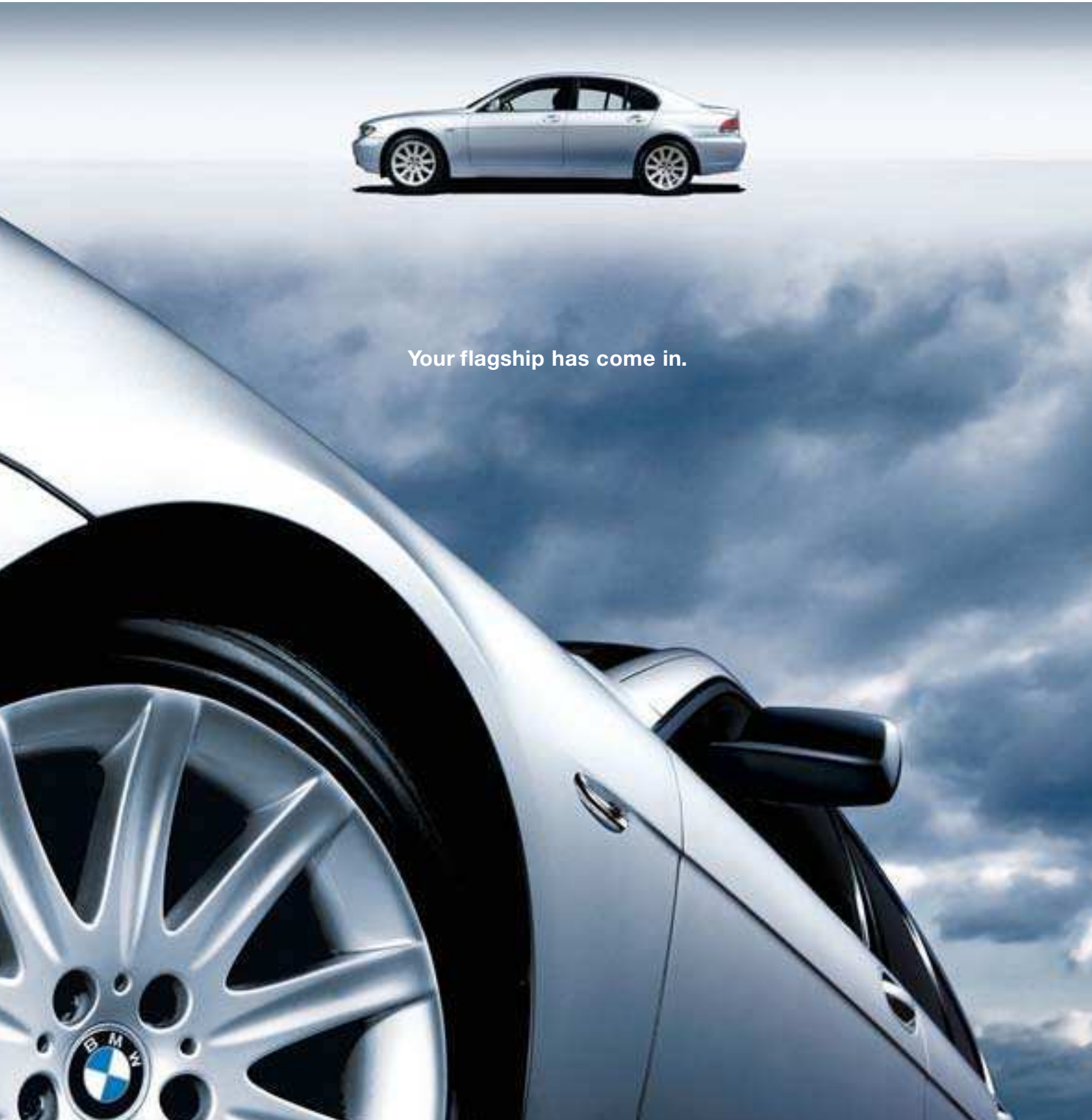
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